Photogrammetric Dimensioning of Ships' Engine-room Models

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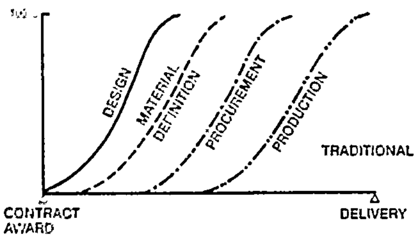
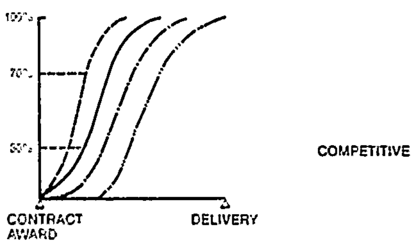
FOREWORD





This book describes how *photogrammetry* can be used to effectively link *design modeling* and *computer-aided piping design systems.* The linkage is important, because traditional design procedures impede the implementation of proven, cost-effective shipbuilding methods.

The world's leading shipbuilders improved their competitive positions significantly by:

- performing design as an aspect of planning, and
- accelerating the design process.

This assisted them in greatly reducing the duration and manhours required to build a ship. They developed, and are continuing to develop, new techniques for converting a design into fabrication and assembly work instructions. These are mostly in the form of digital rather than geometrical drawings. As they are sufficient for ship repair, they have already been accepted by some owners in lieu of costly and time-consuming system and/or composite arrangement drawings. In some cases design manhours spent, were reduced to ¼ of those needed by traditional design organizations.

Most shipbuilders, paradoxically even some traditionalists, employ sophisticated computer-aided design systems. However, none are known to have effectively applied them to the *creative* phase which involves arrangement of pipe pieces and other engine-room components consistent with both:

- functional requirements, and
- need to idealize work packages for on-unit, on-block and on-board outfitting.

For these purposes, even some of the most competitive shipbuilding firms still rely upon manual drawing methods which feature:

- designers organized by zones in lieu of systems,
- cadres of managers, designers and field engineers who are trained in the same shipbuilding philosophy and who can think analytically about industrial engineering matters, and
- techniques such as the application of standards, design modules and arrangement zones that permit effective reapplication of prior experiences.

Where such capabilities do not exist or are diminishing, shipbuilders are employing design modeling for *creating* fitting arrangements of ships' engine-rooms. Some have also interfaced design modeling with computer-aided piping design systems because there are no better methods for quickly and accurately preparing material lists, work instructions, manpower budgets, etc. Various interface methods, described in Appendix B, entail lifting 3-dimensional coordinates from modeled components and are means for "putting" a model, an inherently interference-free data base, into a computer.

None of the dimensioning methods in current use are entirely satisfactory. Although photogrammetric approaches have been evaluated before, the method described herein is uniquely ideal because:

- It was developed by a practicing photogrammetrist having prior shipbuilding experience who learned about pipe design, material requirements, fabrication and assembly matters through visits to shipyards and a worldwide literature search,
- the real design model employed was ingeniously sectionalized and thus provided good "camera" access, and
- modern-day, computer-controlled stereoplotters facilitate 3-dimensional digitizing of anything that can be seen in photographs of a model, a mock-up or a full-scale installation.

ACKNOWLEDGEMENTS

The authors are J.F. Kenefick and L.D. Chirillo respectively of john f. kenef Photogrammetric Consultant, Inc. and Todd Pacific Shipyards Corporati Seattle Division.

The research was performed by john f. kenefick Photogrammetric Consulta Inc. of Indialantic, Florida assisted by Bosworth Aerial Surveys, Inc. of La Worth, Florida.

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1.0 INTRODUCTION

1.1 Background

Where shipbuilding is most competitive, methods and skills have been developed so that design processes are truly aspects of planning. A typical such process for detail design of a machinery space is an ideal example.

Immediately after preparation of separate system diagrammatics, the diagrams are arranged together, sometimes freehand, in order to quickly relate systems and zones; see Figure 1-1. Such relatively rough piping, component and wiring arrangements are the bases for preparation of detail fitting arrangements which are complex composites as shown in Figure 1-2. Representations therein for individual fittings are simplified but, nonetheless, are sufficient for:

- providing the configuration of each fitting,
- listing required materials, and
- identifying the positions of fittings relative to each other.

This sophisticated design approach is especially beneficial because:

- it accelerates the design process and can be performed with as few as a quarter of the manhours needed by traditionalists (there is no investment in unnecessary system arrangement drawings),
- detail designers incorporate essential production-control measures, e.g.:
  - structured material lists,
  - classification of work packages by zone/area/stage as for the Zone Outfitting Method (ZOFM), and
  - identification of pipe pieces as needed for Pipe Piece Family Manufacturing (PPFM), and
- the composites are formats for continually improving and reapplying work packages for different size and type ships when zone/area/stage classifications correspond.[1]

However, this design process which best serves shipbuilders is critically dependent upon very experienced people, continually interacting, who can prepare or decipher the complex fitting arrangement drawings.

During the last ten years, some shipbuilders in Japan and Europe perfected *design modeling* (also called model engineering), as a means for employing less experienced people for producing and conveying designs of ships' machinery spaces.[2] This also included a few shipbuilders having people skilled in the preparation and use of complex composite drawings because:

- the requirement to reflect more understanding of fabrication and assembly techniques in drawings requires more skilled people whereas maintaining existing skill levels is difficult,
- minimizing elapsed time between contract award and delivery, a very strong competitive aspect, requires faster and simpler design methods, and/or
- designing three-dimensional complex representations with a two-dimensional medium without error, is difficult (in some cases a drawing reviewer's endorsement is meaningless whereas models are inherently interference free).

Uniquely, these shipbuilders developed a relatively pure form of design modeling. In their methods, given a model that sufficiently reflects hull structure and a machinery arrangement, designers who have acquired modeling skills create details for distributive systems directly in the model using guidance such as:

- roughly arranged diagrammatics, and
- a pallet list, i.e., a sequence for work packages designated by zone/area/stage, adapted from a previous ship construction project.

This use of models is markedly more productive than general U.S. practice wherein a model is built after or

[1]Zone outfitting, family manufacturing and zone/area/stage classifications are as featured in the publication "Product Work Breakdown Structure—November 1980" by Y. Okayama and L.D. Chirillo for the National Shipbuilding Research Program.

[2]Italicized words and terms throughout the text of this book are defined in Appendix A.

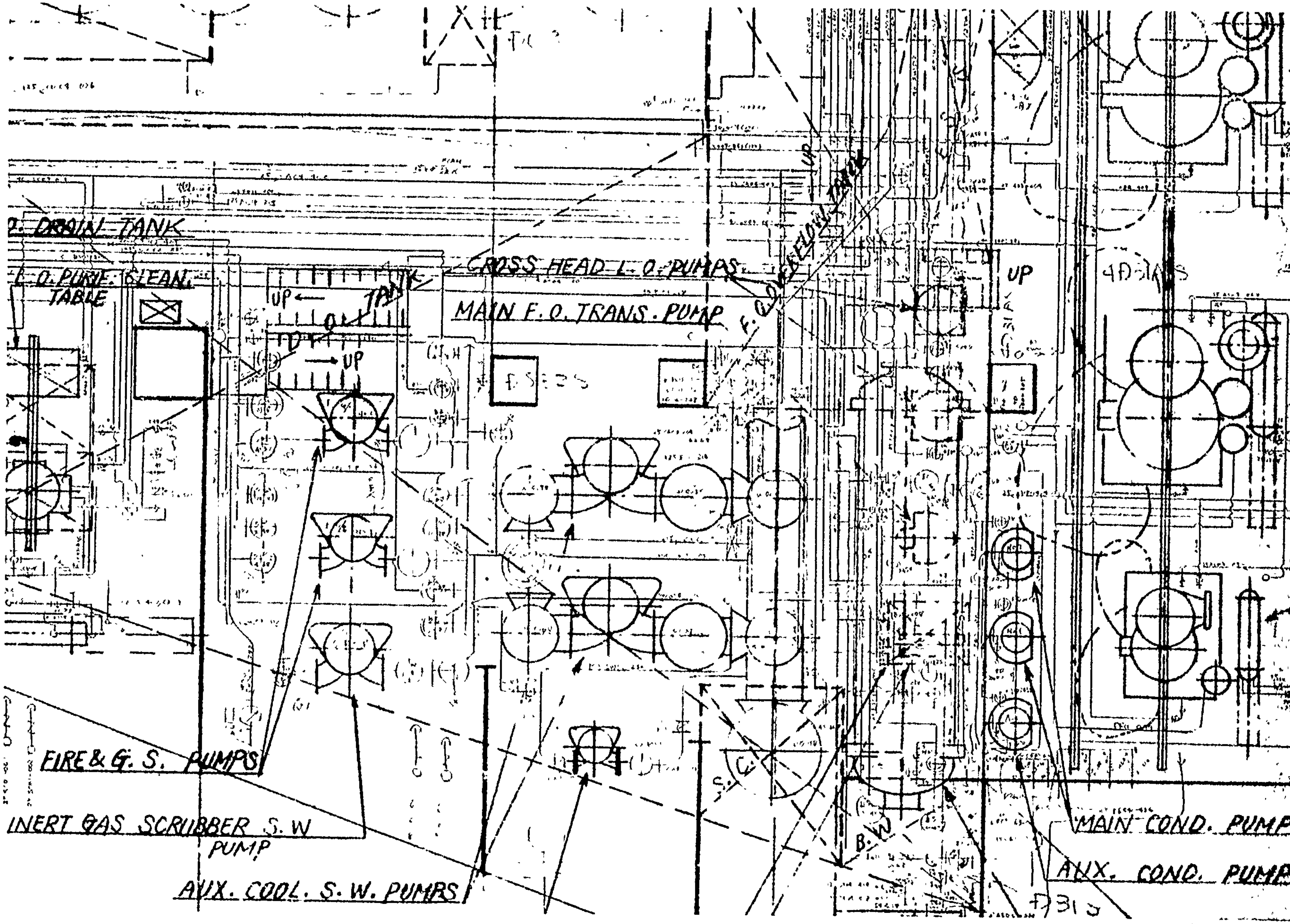

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FIGURE 1-1: Outfit Transition Design. In order to quickly relate systems and zones, machinery-space arrangement specialists arrange diagrammatics together. Relative positions of distributive systems, including fittings such as valves, are frequently adapted from a file of design modules and/or anticipate work packages classified by zone/problem area/stage.

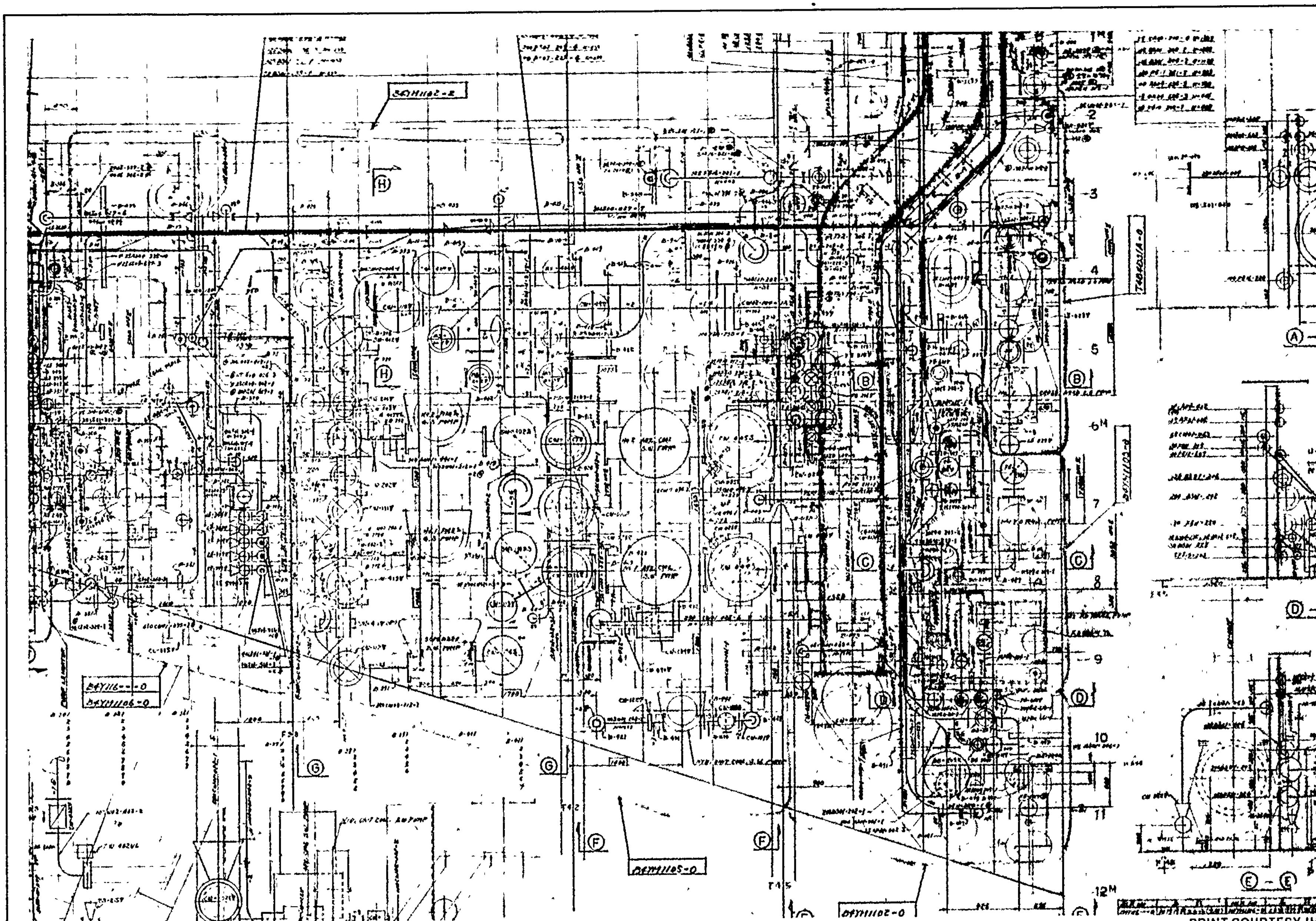

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FIGURE 1-2: Detail Fitting Arrangement. This composite drawing is marked to show zone demarcations. Zone/problem area/stage classifications are coded in the work package numbers such as B4YM1102-0 which appears near the bottom of the figure. Each pipe piece is represented by a single line. Certain dimensions, such as elevations for pipe supports, are omitted as they are based upon standards and specific dimensions which are separately furnished to subcontractors.

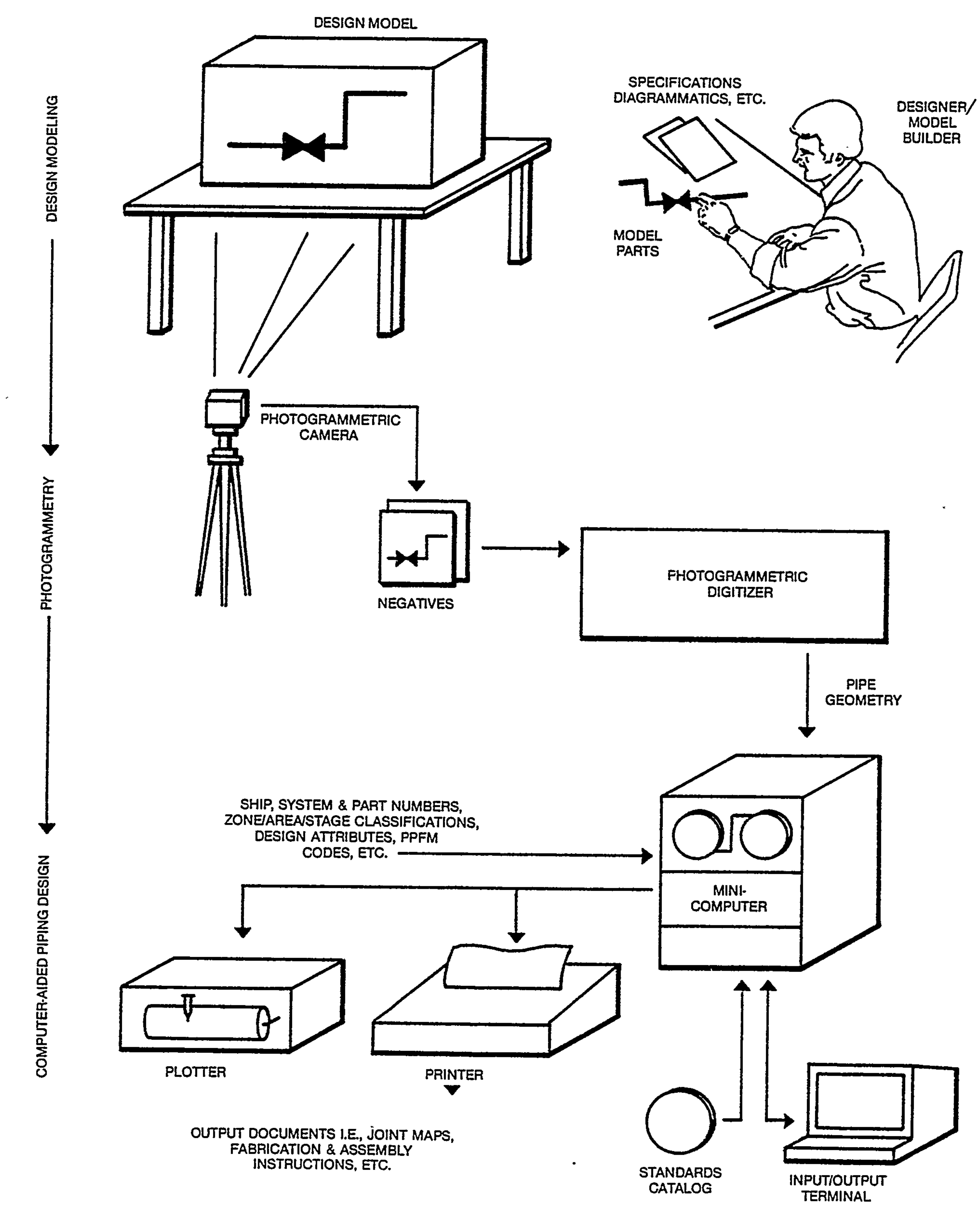


FIGURE 1-3: The Marriage of Design Modeling, Photogrammetry and Computer-Aided Piping Design Systems.

simultaneously with the preparation of system arrangement and/or composite drawings and is relied upon mostly for detecting and resolving interferences. Shipbuilders who subscribe to such practice are paying twice for the same function and are unnecessarily retarding design progress because a model contains all systems and is a composite.

Even for moderately complex arrangements and especially where detail designers remain organized by system instead of zone, maintaining drawings sufficiently in unison with a model and vice versa is improbable. Designer/modelers, not so encumbered, are more free to address design *attributes* which facilitate fabrication of parts and assembly work.

Also, design modeling as developed by shipbuilders abroad is different from that usually associated with petrochemical plants in that designers do not label each component with definitive coordinates. This procedure is avoided because manually measuring, labeling and the subsequent take-off of information are laborious and difficult tasks that are very susceptible to human error.

More exact and practical methods for lifting dimensional data from design models has been given significant attention principally by Japanese and European shipbuilders. Appendix B describes such approaches, some of which are being practiced. Only one is a *photogrammetric* solution. Although it was well thought out, a *digital*-photogrammetric approach was not then practical because *digitizing hardware* was still on the threshold of development. An understanding of the concepts of these alternate approaches supports opinion that modern photogrammetric processes are now practical for obtaining and automatically recording dimensions from models.

1.2 Credibility of Photogrammetry

The credibility of photogrammetry, the science of obtaining reliable three-dimensional measurements from photographs, was established for shipbuilders by earlier research which described demonstrations in real production situations.[3] Implementation within several U.S. shipyards was relatively instantaneous. At least seven have used photogrammetric surveys of large structures on a recurring basis and six others have had such surveys performed for one-time special applications. Credibility has even overflowed into naval shipbuilding, ship repair and both the offshore and aircraft industries.

Although primarily concerned with surveys of large structures, the earlier research also demonstrated a photogrammetric method for producing an accurate composite arrangement drawing from a model of a ship's machinery space. Having been required to learn about related shipbuilding methods, the photogrammetrist then concluded:

> "Since a *stereoplotter* measures in all three dimensions simultaneously, and since each axis can be digitized, the points defining a pipe piece can be digitized...details could be automatically generated as has been demonstrated elsewhere. The *digital* data could be merged with other automated design systems...it is clear that photogrammetry could serve as an excellent input device which would permit a combined designer/model maker to put inherently interference-free piping arrangements into a computer."

1.3 Approach

Since design modeling, photogrammetry and *computer-aided* detail design were being separately applied by shipbuilders, the work described herein was limited to development and demonstration of a practical method for combining the three disciplines; see Figure 1-3. Only pipe systems were considered as the photogrammetric processes for other distributive systems would not be substantially different.

As minimal preparation the photogrammetrist was required to:

- develop an understanding of design modeling via personal observations and a literature search,
- become familiar with processes for design of ships' distributive systems,
- acquire a basic understanding of pipe-piece fabrication data and how they are generated and applied,
- learn about prerequisites for bills-of-material, and
- study the input requirements and capabilities of existing computer-aided pipe-piece detailing programs.

The development work was performed using part of a design-model of a ship's engine-room, shown in Figure 1-4, which was obtained from a Japanese shipbuilding firm that employs a complete model-engineering system.[4]

A general digitizing scheme was developed and applied as described in Chapter 2.0. Virtually all piping details were extracted from a typical section of the model. As digitizing was performed within several *stereopairs* of photographs taken from different vantage points, no critical data was lost due to obscurations. Because it was only necessary to digitize random points on a pipe's surface (and later fit a cylinder to the points), portions of a pipe's surface appearing in any stereopair were generally sufficient.

[3] "Photogrammetry in Shipbuilding—July 1976" by john f. kenefick Photogrammetric Consultant, Inc., Indialantic, Florida; for the National Shipbuilding Research Program. Available as publication No. PB-262-130/AS from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

[4] Hitachi Shipbuilding & Engineering Co., Ltd., Osaka, Japan.

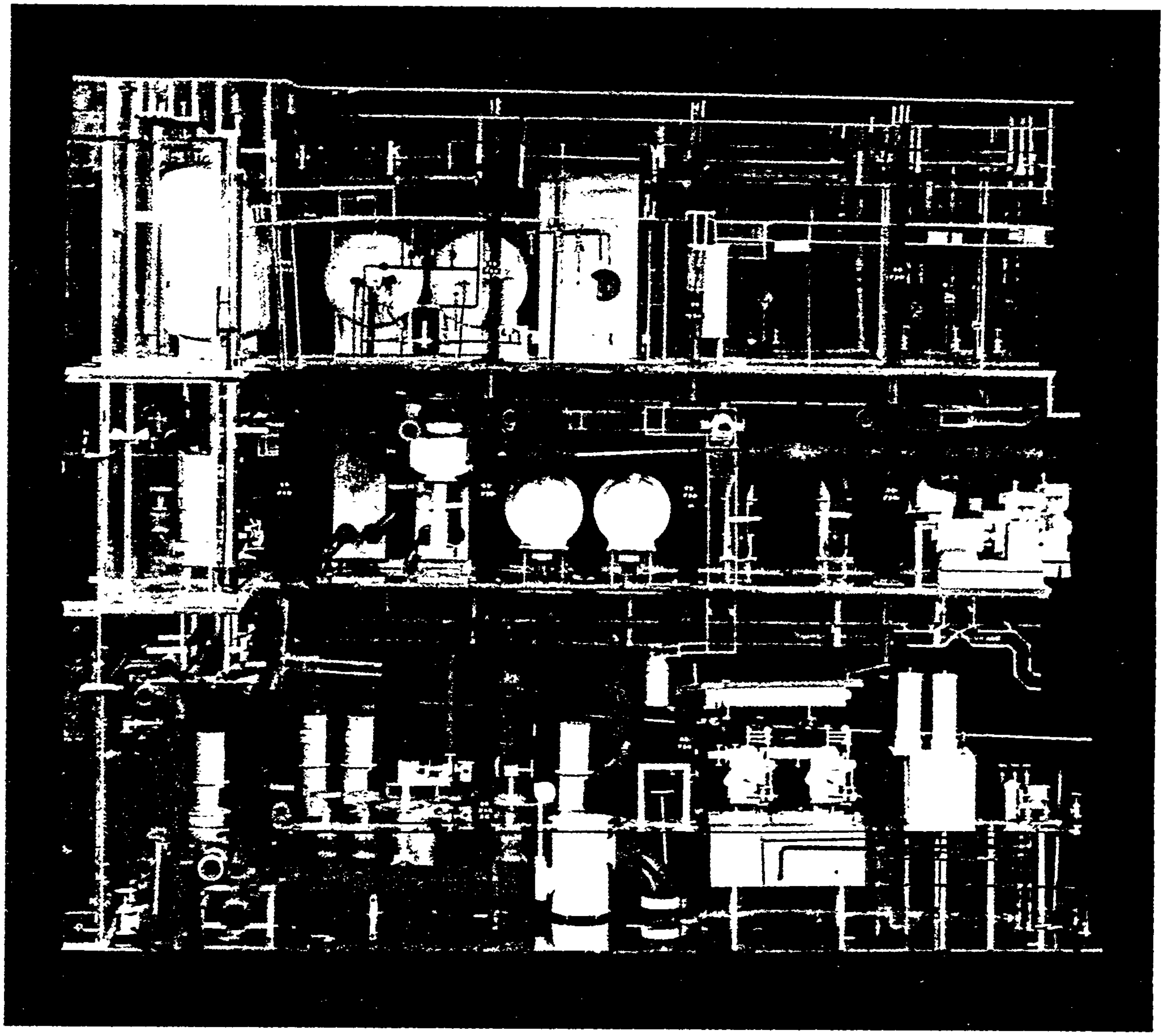


FIGURE 1-4: Design Model of a Ship's Engine Room. This model, consisting of a stack of six separable sections, was built by designers in lieu of preparing fitting-arrangment drawings. It includes just the machinery, piping and fittings arranged starboard and outboard of a main-propulsion diesel engine for an 18,930 DWT container ship. The model was used for final test of a developed system for photogrammetric dimensioning. Although this 1:15 scale model was built in Japan, many of its components were procured from Engineering Model Associates, Inc., City of Industry, California.

1.4 Findings

The salient conclusion is that photogrammetry does provide a productive means for obtaining accurate dimensions from models, particularly when compared to other methods being applied by shipbuilders abroad as described in Appendix B.

1.4.1 Accuracy

The photogrammetric method applied is inherently accurate. Verification was facilitated because the 1:15 scale model was sectioned with each section mounted on a separate base. A grid, scribed by a designer, upon each base provided perfectly defined points for fixing distances varying from 5 to 19 inches (6'-3" to 23'-9" at full scale). Using one model section, fifteen such distances were so defined by targets. Each distance was photogrammetrically determined four times using stereopairs taken from as many different views. Thus, the accuracy verification sample contained sixty measurements. Comparisons between the photogrammetrically and manually obtained measurements between grid intersections produced:

- an average difference of 0.20 inches at full scale, and
- a maximum difference of 0.59 inches at full scale.

However, model components contain few discrete points such as defined by a grid. Thus, for comparison purposes, it was not practical to obtain reliable manually derived dimensions of piping details within the model. Manual measurements are inherently inaccurate because:

- needed physical access is impeded by congestion of model details,
- pipe-bend intersection points are virtual, and
- locations of bend-intersection points are subject to interpretation, particularly for bends less than 90°.

In contrast, photogrammetric measurements are reliable because:

- they depend on photographic access (anything that can be seen can be measured regardless of congestion), and
- pipe centerline and bend-intersection points are precisely calculated from digitized points on pipe surfaces.

Since better references were not available, the results of the photogrammetric dimensioning process are reported relative to their corresponding manually obtained dimensions. Nonetheless the results are noteworthy.

Coordinates of pipe-bend intersection points computed from photogrammetric measurements were used to calculate distances between pairs of adjacent bend intersections. These were compared to corresponding distances measured by hand on the model. The average full-scale difference was 0.33 inches and the maximum full-scale difference was 1.58 inches. Similar checks were made of the locations of pipe *events,* i.e., each of their locations distance-wise from the nearest bend intersection. The average full-scale difference was 0.50 inches with a maximum full-scale difference of 1.10 inches.

These reported differences are inherently pessimistic because of uncertaincies in the manual measurements as described in the foregoing. Differences resulting from the initial accuracy check using grid points are the most optimistic results expected. Actual differences for piping detail, i.e., based upon true dimensions in the model, if they could be determined, would be closer to those reported as the most optimistic. However, in practical applications, photogrammetry is more likely to be employed for the transfer of a model as a data base into a computer. Thus any of the differences reported, pessimistic or otherwise, should be of no concern because existing computer programs for pipe design readily make adjustments.

Model scale also impacts on accuracy. For example, the excellent results obtained could not have been achieved with a 1:24 scale model, whereas, better accuracy would have been achieved if a 1:10 scale model had been used. Obviously, accuracy would be best at 1:1 scale, e.g., when dimensioning photogrammetrically from a full-sized mock-up or an actual piping installation.

1.4.2 Costs

The model, consisting of six sections, contained 230 pipe *segments* and 160 pipe events. Based upon defining the piping geometry in the most representative model section, the estimated cost for photogrammetric dimensioning the piping and pipe events in all six sections is $9,145 (circa 1980). This estimate is based upon using a process featuring a computer-controlled stereoplotter but otherwise as described in Chapter 2.0. Further development of the software used for the demonstration could reduce the estimated cost by as much as 15%.

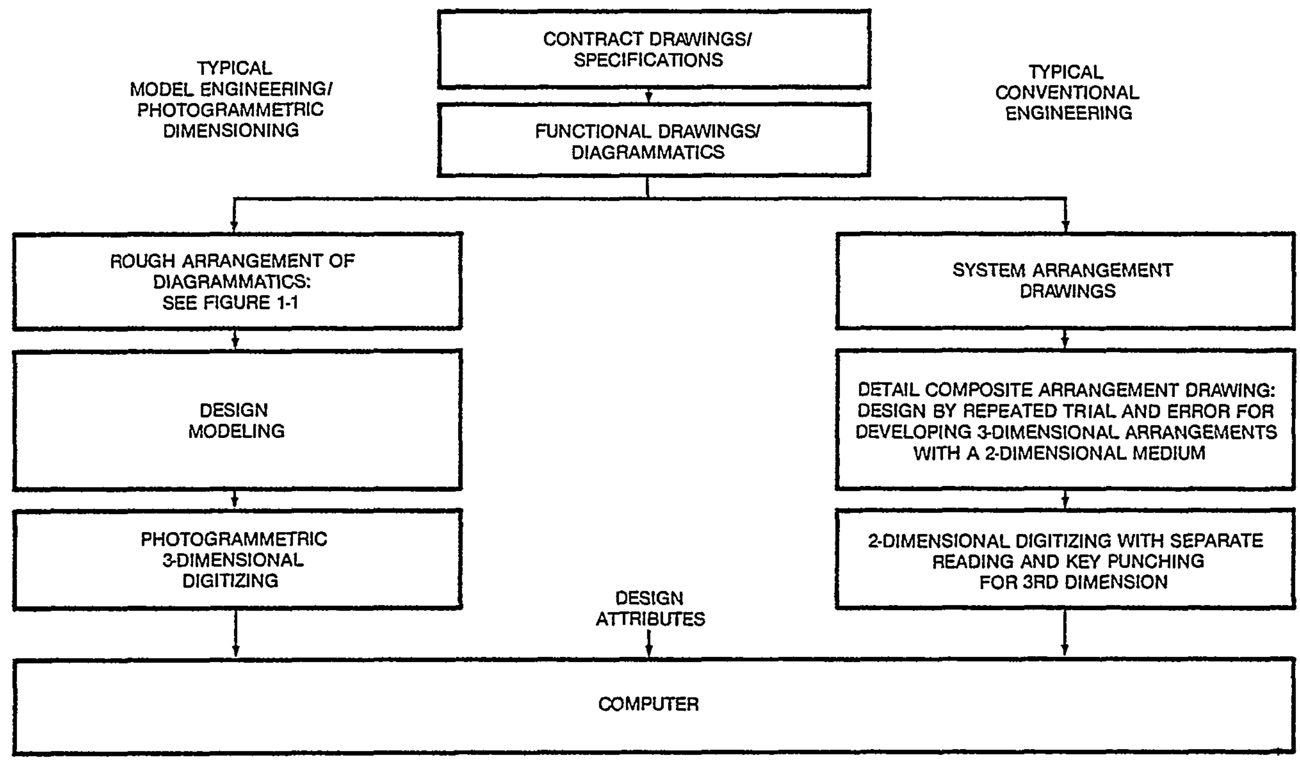


FIGURE 1-5: Model Engineering/Photogrammetric Dimensioning vs. Conventional Engineering Systems. Some shipbuilders throughout the world adopted model engineering because they are experiencing or expect shortages in the numbers of people qualified in conventional engineering methods.

Approximately 56% of the total estimate is burdened labor at $20/hour. Of this, half is for skills that most shipbuilding firms have in house. The remaining 44% of the total estimate, other than $600 for photographic supplies, consists of fees for equipment rentals. This includes about $1,400 for time on a computer such as those that shipbuilders already employ.

Figure 1-5 shows how a model engineering system featuring photogrammetric dimensioning compares to a conventional engineering system. As shown, three pair of functions, not just photogrammetry, justify comparisons. In making judgements, managers in shipyards which still employ conventional design processes should keep in mind that:

- shipbuilders who shifted to design modeling and automated means for dimensioning from models, did so because they anticipated shortages of experienced people skilled in detail design (in 1980 at least one U.S. shipbuilder resorted to advertising abroad for qualified draftsmen), and
- simplification of design processes becomes more urgent if more planning is to be performed by designers, e.g., zone/area/stage classifications and structured material lists as in the world's most competitive shipyards.

Estimated costs for photogrammetric *hardware* and sources of both photogrammetric hardware and services are included in Appendix C.

2.0 THE DEVELOPED PHOTOGRAMMETRIC SYSTEM

2.1 System

In order to devise a practical photogrammetric method for dimensioning from models, pure *analytical* photogrammetry was considered as was a system in which measurements would be taken from a *stereomodel.* During evaluations of alternatives the following desirable characteristics, some also applicable for non-photogrammetric methods, were noted:

(a) The same basic system and procedures should be used regardless of whether the model is true-to-scale or *wire-and-disc.*

(b) Drastic changes in conventional model building techniques should not be required.

(c) Custom-built photogrammetric hardware should not be required.

(d) The camera should be focusable over a range of distances and should have liberal depth-of-field.

(e) Extensive preparation of the model should not be required.

(f) Extreme care in positioning the camera or the model should not be required.

(g) Black and white photographs should be used.

(h) Gathering of raw data (i.e. taking photographs) should be fast so as not to interfere with model use by others.

(i) The procedures for digitizing from photographs should be simple so that an expert photogrammetrist would not be needed.

(j) The digitizing instrument should not be significantly limited by focal length, allowable distance between *camera stations* and lack of parallelism between optical axes of adjacent photographs.

(k) The output should consist of digitized coordinates of pipe bend-intersection points and centerline locations of pipe events.

(l) The accuracy of coordinate data produced by the system should be sufficiently compatible with fabrication and assembly requirements.

(m) The format for obtained data should be compatible with input requirements of existing computer-aided pipe detailing and fabrication programs.

(n) If possible, the photogrammetric equipment should also be usable for other shipyard measurement tasks such as dimensioning large structure (hull mid-bodies, submarine circularity, LNG tanks, offshore platforms, sonar domes, pipe-closing pieces, large castings, etc.).

Consideration of the foregoing was the basis for determining that the best solution would use a computer-controlled *stereoplotter* to *encode* and record three-dimensional digitized data from a stereomodel. Pipe centerlines, bend-intersection points and centerline locations of pipe events would be accurately calculated from selected points on modeled surfaces. This indirect approach would permit usage of molded-plastic components that are readily available from industrial-model supply firms.

2.2 Models

Initial experiments were conducted with part of a model of a floating nuclear-power plant.[1] They were the basis for developing and evaluating proposed procedures. These experiments also included tests of the computer programs prepared for reducing digital data of pipe surfaces and events into needed coordinates such as for pipe-bend intersection points and centerline locations of pipe events.

While the experimental work was in progress, arrangements were made to obtain sections of a 1:15 scale real design model. It was used to design an engine room of an 18,930 DWT diesel-propelled container ship and had been built in sections in order to provide visual access for an *orthographic* camera.[2] The model was uniquely divided into twenty-five sections of which six, designated in Figure 2-1, were sufficiently representative for evaluating photogrammetric dimen-

[1]Loaned by Offshore Power Systems, Jacksonville, Florida.

[2]See "Development of the Draft Camera—A New Camera for Orthographic Photo Drawings" by Y. Tomita of Hitachi Shipbuilding & Engineering Co., Ltd.; Osaka, Japan; Proceedings of The American Engineering Model Society May 1979 Seminar, San Francisco, California, pp. 7-30.

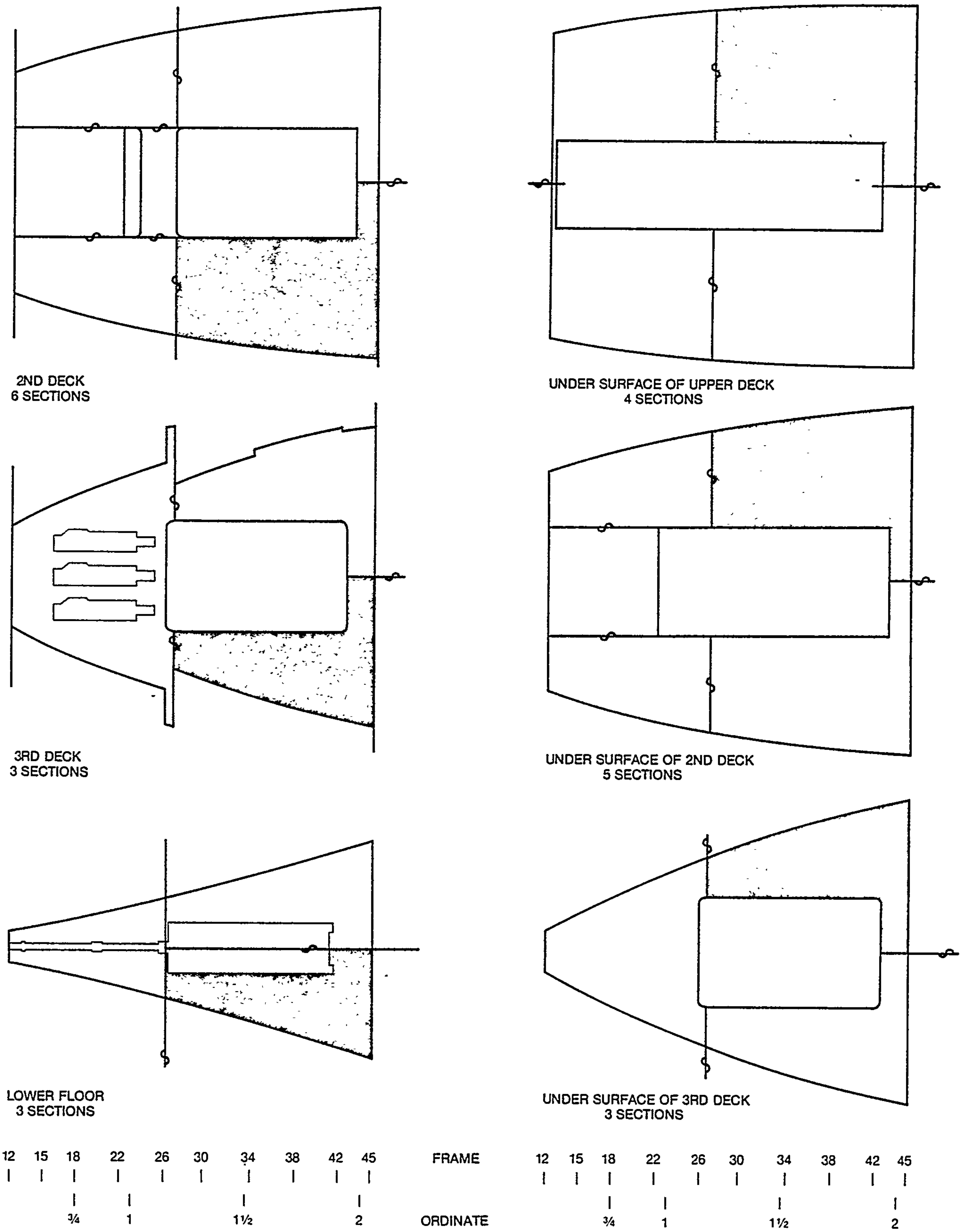


FIGURE 2-1(a): Typical Model Division Scheme. Design models developed by engineers in Hitachi Shipbuilding & Engineering Co., Ltd., are ideal for photogrammetric dimensioning because they are ingeniously sectionalized for visual access. The six shaded sections were obtained for the demonstration of photogrammetric dimensioning.

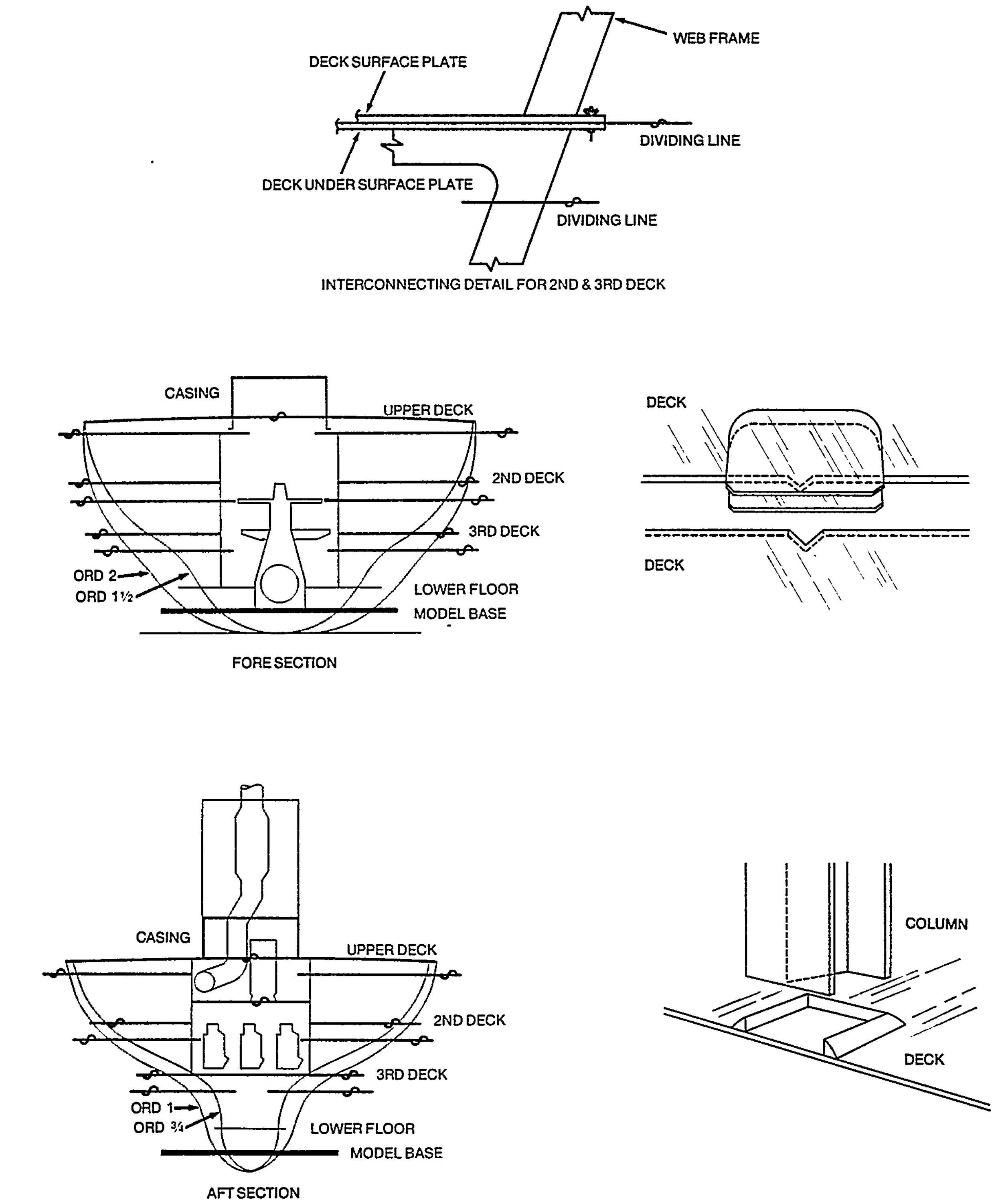


FIGURE 2-1(b): Various model building techniques are used by Hitachi's machinery-space arrangement designers which facilitate quick separation of the sections and their accurate alignment during reassembly.

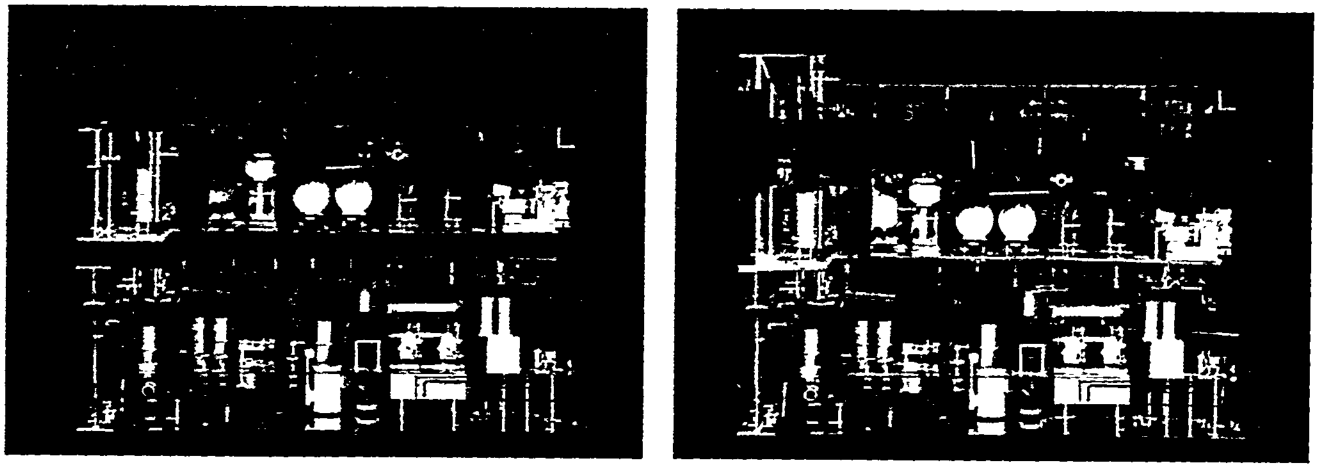


FIGURE 2-2: Separation of Model Sections. *Left:* Separation through the 3rd deck. *Right:* Separation at a plane between the 2nd and 3rd decks. Each model section anticipates outfitting on-block with ceilings outfitted down hand when blocks are upside down. For larger ships, detachable subassemblies which anticipate outfitting on-unit would be included.

sioning. Because the sections could be readily separated, as shown in Figure 2-2, they were easier to construct than conventional models. But more important, they provided greatly improved visual access. Plan views of each of the six model sections are shown in Figure 2-3.

2.3 Model Preparation

During their construction, a reference grid was scribed upon the base of each model section and also on vertical surfaces wherever practical. Thus, distances corresponding to waterline, buttock and frame spacing were conveniently incorporated (at 1.0, 1.0 and 0.8 m respectively at full scale). These provided absolute reference for the photogrammetric solution. *Targets* were fixed on selected grid intersections so that these "known" locations would be readily seen on photographs. Two target types were employed as described in Figure 2-4.

In order to accurately merge data from the several different photographic views required of each model section, additional finely defined points likely to be seen in all views were selected. These served only to "tie-in" the camera positions relative to each other and to the model section photographed. Discrete marks in each model section were used for this purpose. Had there not been enough discrete marks, special "tie-in" targets would have been added. A few of the targets placed at grid intersections to provide absolute references, were visible in more than one or two views and thus served also as "tie-in" targets.

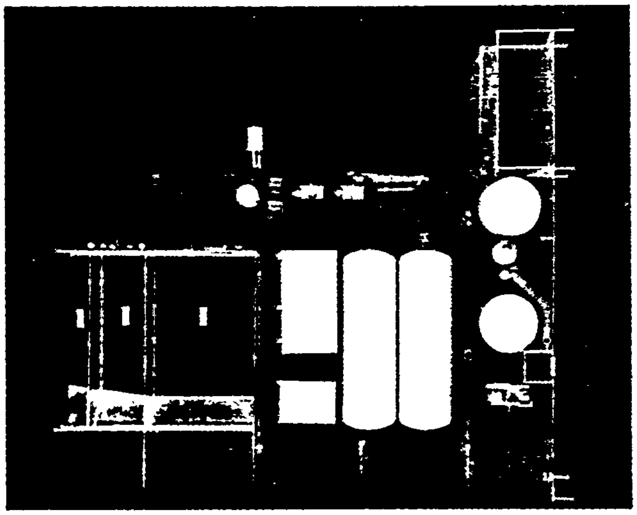
2.4 Photography

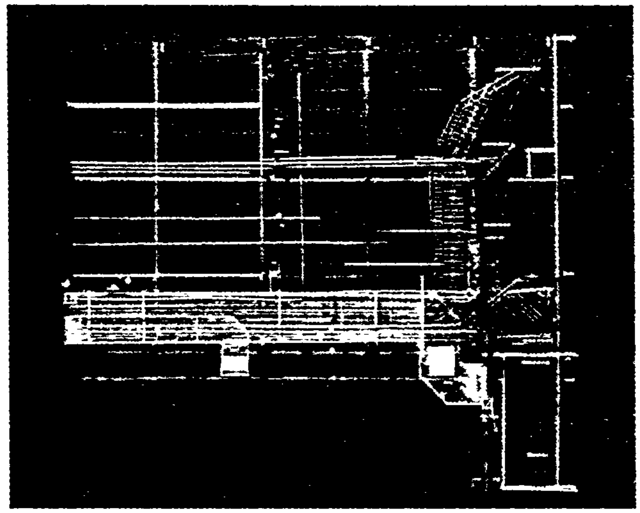
2.4.1 Camera

All photographs were taken with a Wild P31 Universal Terrestrial Camera; see Figure 2-5. This particular camera was employed because of its ready availability and suitability for close-up photography of models. A similar camera manufactured by the Zeiss Jena Works (model UMK 10/1318) might have been better suited because of its greater depth-of-field. Both the Wild and Zeiss cameras feature virtually distortion-free lenses and means to accept sensitized glass plates as well as film. Glass plates were used throughout the demonstration because of their dimensional stability. However, the results achieved indicate that film, cheaper and easier to handle, would be practical.

2.4.2 Camera/Model Geometry

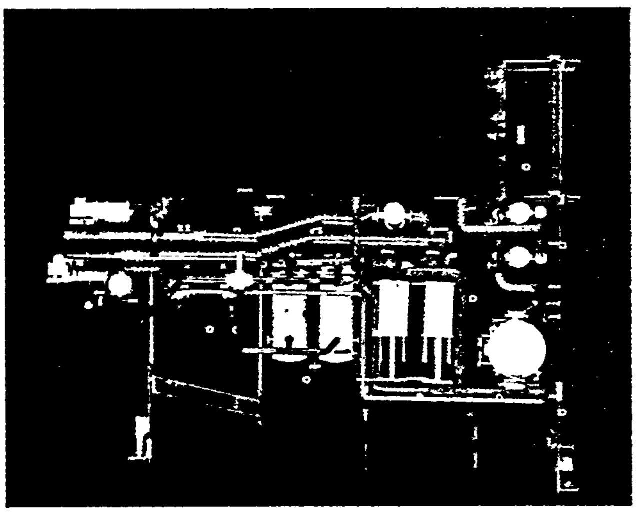
Rough calculations performed in advance indicated that a reasonable set up of camera stations relative to the model could be such that a single stereopair would cover an entire model section. The basic tradeoff involved decreasing the camera-to-object distance for greater accuracy while increasing the number of required photographs owing to depth-of-field limitations at short ranges. Additional photographs involve higher costs primarily because they require more data reduction.

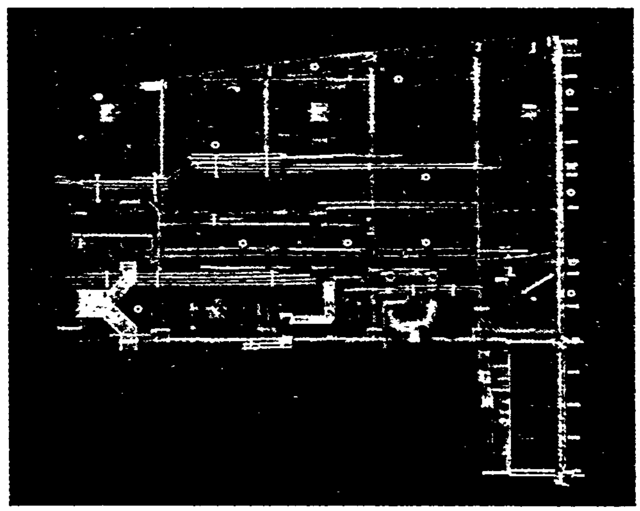




2ND DECK

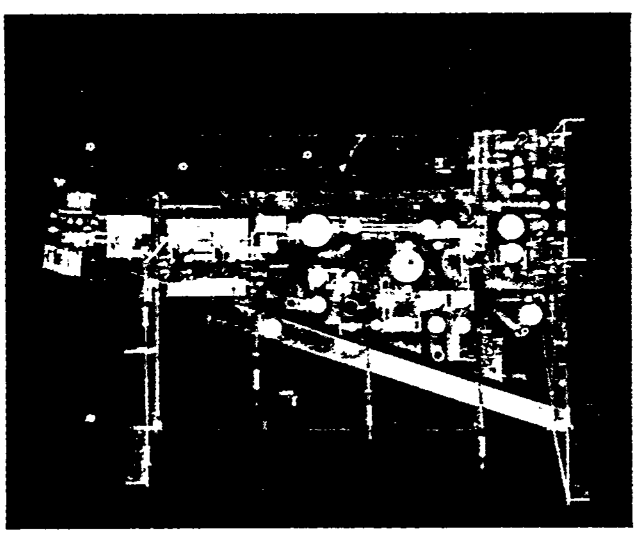
UNDER SURFACE OF UPPER DECK

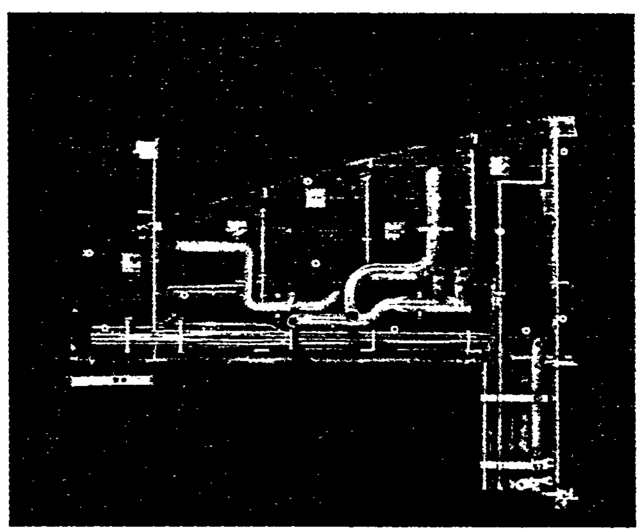




3RD DECK

UNDER SURFACE OF 2ND DECK





LOWER FLOOR

UNDER SURFACE OF 3RD DECK

FIGURE 2-3: Six Adjoining Model Sections. These sections correspond to those designated by shading in Figure 2-1(a).

FIGURE 2-4: Targets for Known Ship-Coordinates. *Left:* A target which was printed on peel-off self-adhesive paper. Its registration marks are aligned with the grid lines scribed on the base of a model section. *Right:* An ordinary gummed reinforcing-ring circles a grid intersection. The scribed lines within were filled with a red pencil to make them more visible. Both target types proved to be satisfactory. The hand-lettered numbers around each target, added for convenience only, are known ship-coordinates.

The geometry of the final set up is in Figure 2-6. As shown, two important additional measures were incorporated:

- Each model section was tilted so as to avoid hiding piping detail as much as possible. If a photograph was taken with the camera axis in a plane parallel to a deck, some piping in the foreground could obscure piping in the background. This is likely because pipes in ships' machinery spaces are often located in common horizontal planes, particularly when suspended from an overhead.

- The distance between each pair of camera stations was necessarily smaller than that needed for ultimate accuracy. As a practical matter, the distance was limited by the need to digitize vertical piping in the foreground while viewing such pipes stereoscopically. If the camera stations were too far apart, the left-hand exposure would have imaged only the left side of a vertical pipe and the right-hand exposure would have imaged only the right side. Absence of common pipe-surface images on both photographs would render it impossible to digitize such pipes because they cannot be viewed stereoscopically.

2.4.3 Procedure

With a model section tilted, as shown in Figure 2-6, a black and white picture was obtained from one of the indicated camera stations. The camera was then shifted to the other camera station for a second photograph. The two comprise a needed stereopair. The model section was then rotated 90° about an axis perpendicular to the model base, and another stereopair was obtained. This process was repeated until a stereopair was obtained from each side of the model section. Further, using an ordinary camera a single color snapshot was obtained from a position approximately midway between

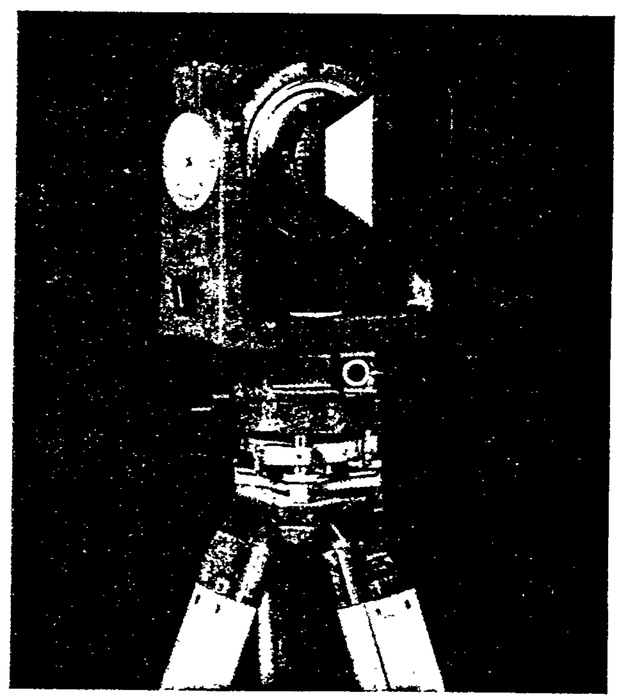


FIGURE 2-5: The Wild P31 Universal Terrestrial Camera. This model accepts single glass or film frames, is focusable over a range of distances and has a distortion-free lens. The camera is often used detached from the yoke/tripod assembly.

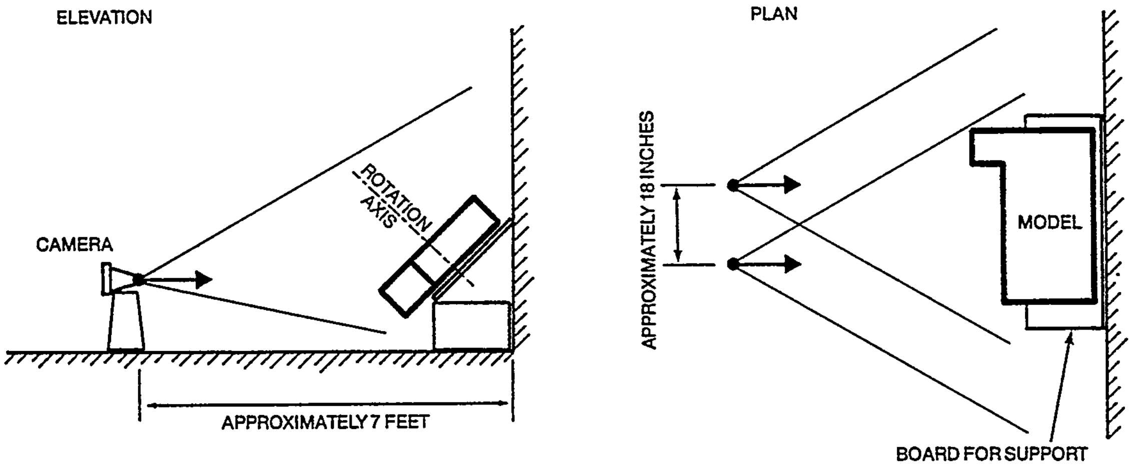


FIGURE 2-6: Camera/Model Geometry. Trade-offs considered involved photogrammetric accuracy, numbers of photographs and depth of field. The model was tilted to avoid obscurations of background detail. One camera was shifted between the two camera stations in order to obtain a stereopair.

the two camera stations for each of the four model views. These were for future reference should the model become unavailable. A set of snapshots showing such views of a model section as rotated, are contained in Figure 2-7. A typical photogrammetric stereopair is shown in Figure 2-8.

While it may seem redundant to photograph each model section from four aspects, the process was fast and worthwhile because of the following:

- No piping detail was lost entirely. Detail obscured in one or two view(s) was seen in the other views.
- Calculations of pipe centerlines were much more reliable because the four stereopairs permitted data to be collected from two or more "sides" of each pipe segment. This greatly facilitated fitting a cylinder to the digitized data.
- Data digitized within any given stereopair had a range of accuracy which decreased from foreground to background detail. When data from the four stereopair were merged, the overall accuracy of all details digitized became more uniform.

2.4.4 Lighting

Bounce lighting of each model section proved to be most effective. This was accomplished by simply directing strobe lights away from each model section. The light which impinged upon each model came from all directions. The images thus recorded were virtually free of shadows which could cause loss of detail or be mistaken for actual pipe segments.

Because bounce lighting scatters light energy, it was necessary to use a fairly high-powered strobe unit for sufficient illumination from a single pulse (1,200 watt-seconds). A digital strobe meter facilitated rapid determination of correct exposures without trial-and-error experiments.

2.4.5 Simplicity

The preparations and procedures employed for the demonstration were very simple. They can be repeated anywhere without a specially prepared room. Although an ideal set up of the model/camera geometry was planned in advance, implementation did not require precise measurements; an ordinary carpenter's tape was used. Bounce lighting was achieved without any special precautions and "eyeball" aiming of the camera was adequate. Figure 2-9 illustrates the set up used to photograph each model section. While the set up may appear experimental, it need not be any more sophisticated for actual production work.

2.5 Preparations for Three-dimensional Digitizing

As a computer-controlled stereoplotter was not readily available for the demonstration, an encoded *analog stereoplotter* connected to a minicomputer was used. It required special precomputations in order to quickly recreate the exact positions and attitudes of one photograph relative to the other in a stereopair. Otherwise, it performed just as if it were a modern-day, totally computer-controlled stereoplotter.

Instructions prepared in advance, by someone with nominal experience in detail arrangements, permitted the stereodigitizer operator to rapidly collect needed data. The operator was thus relieved of the need to make many decisions such as what to digitize, what identifiers to attach to digitized data, and what detail has or has not been digitized. The instructions permitted maximum productivity of the stereodigitizer and of the operator's unique expertise to view stereoscopically and digitize in three dimensions.

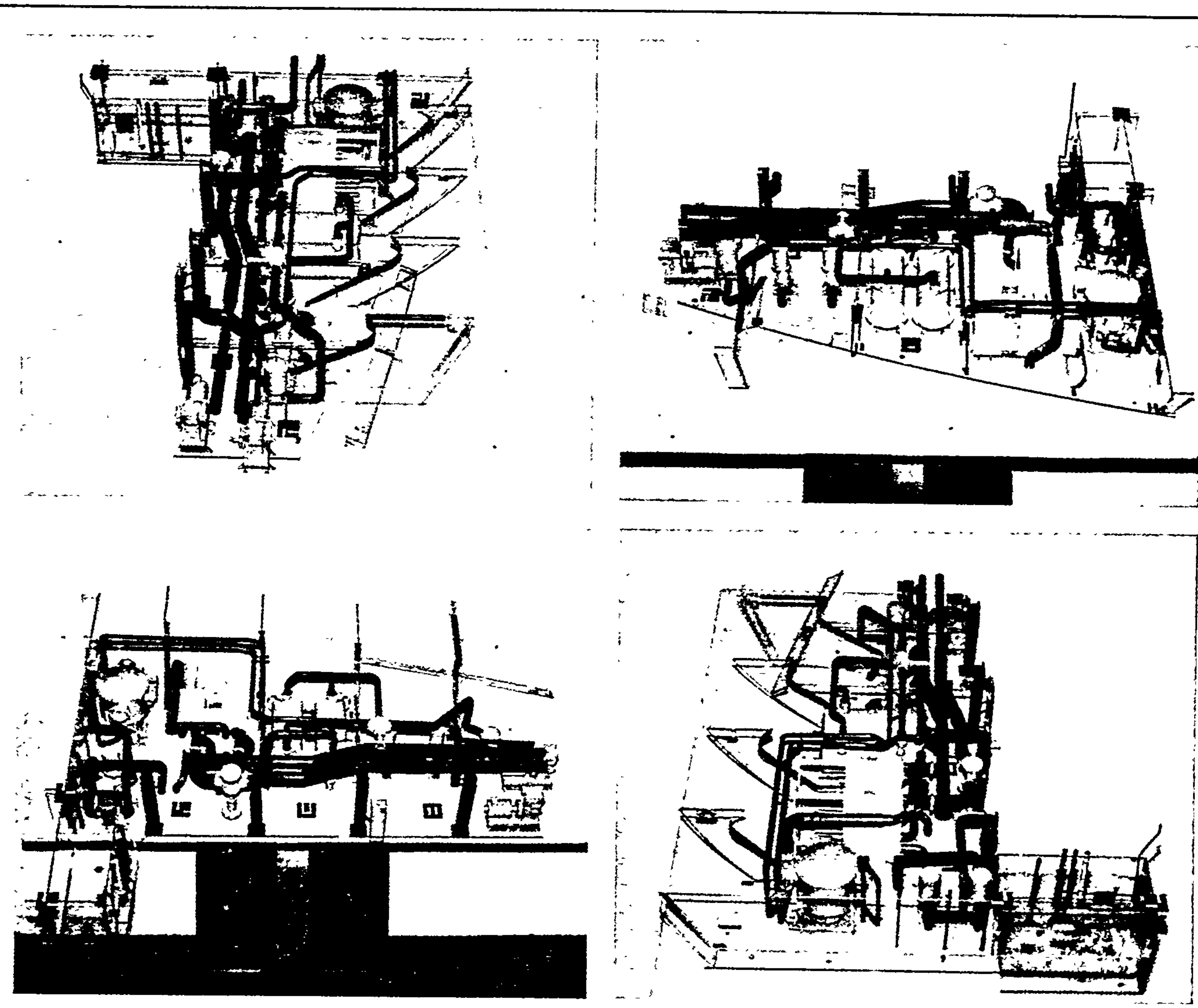


FIGURE 2-7: Rotation of a Model Section. Four different views with the section inclined avoid hidden details and thus show all "sides" of pipe segments. These snapshots, in color, were for future reference should the model become inaccessible.

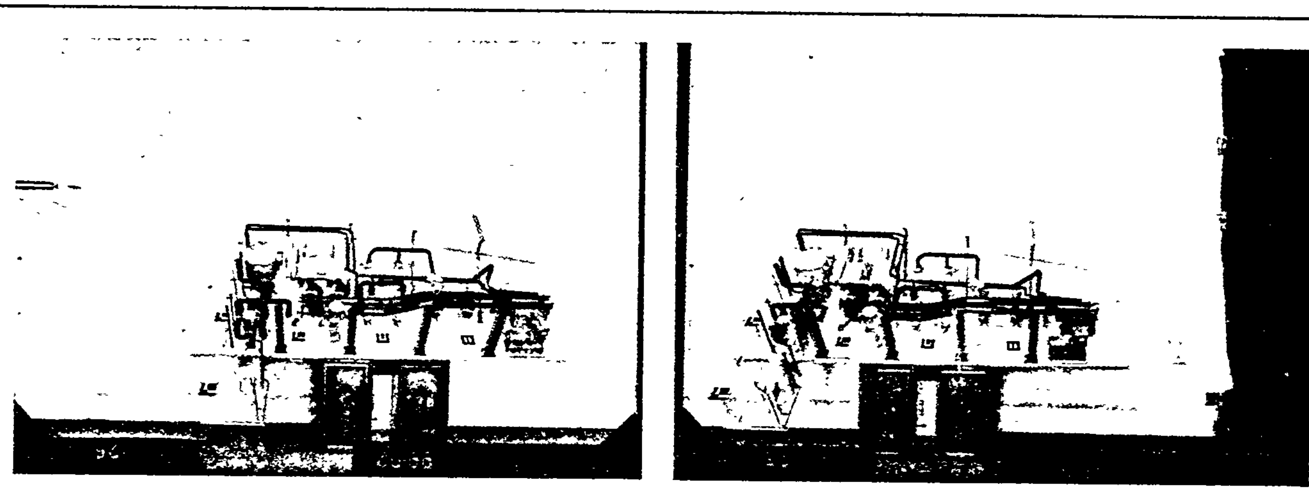


FIGURE 2-8: Stereopair. These are 1:1 prints made from the original glass negatives. The background grid, on mylar, was evaluated for contrast on an otherwise featureless surface and as an aid for orienting a stereopair in a stereodigitizer. Another method which used targets, shown in Figure 2-4, at random locations on the wall, was better because they did not move between photographic exposures.

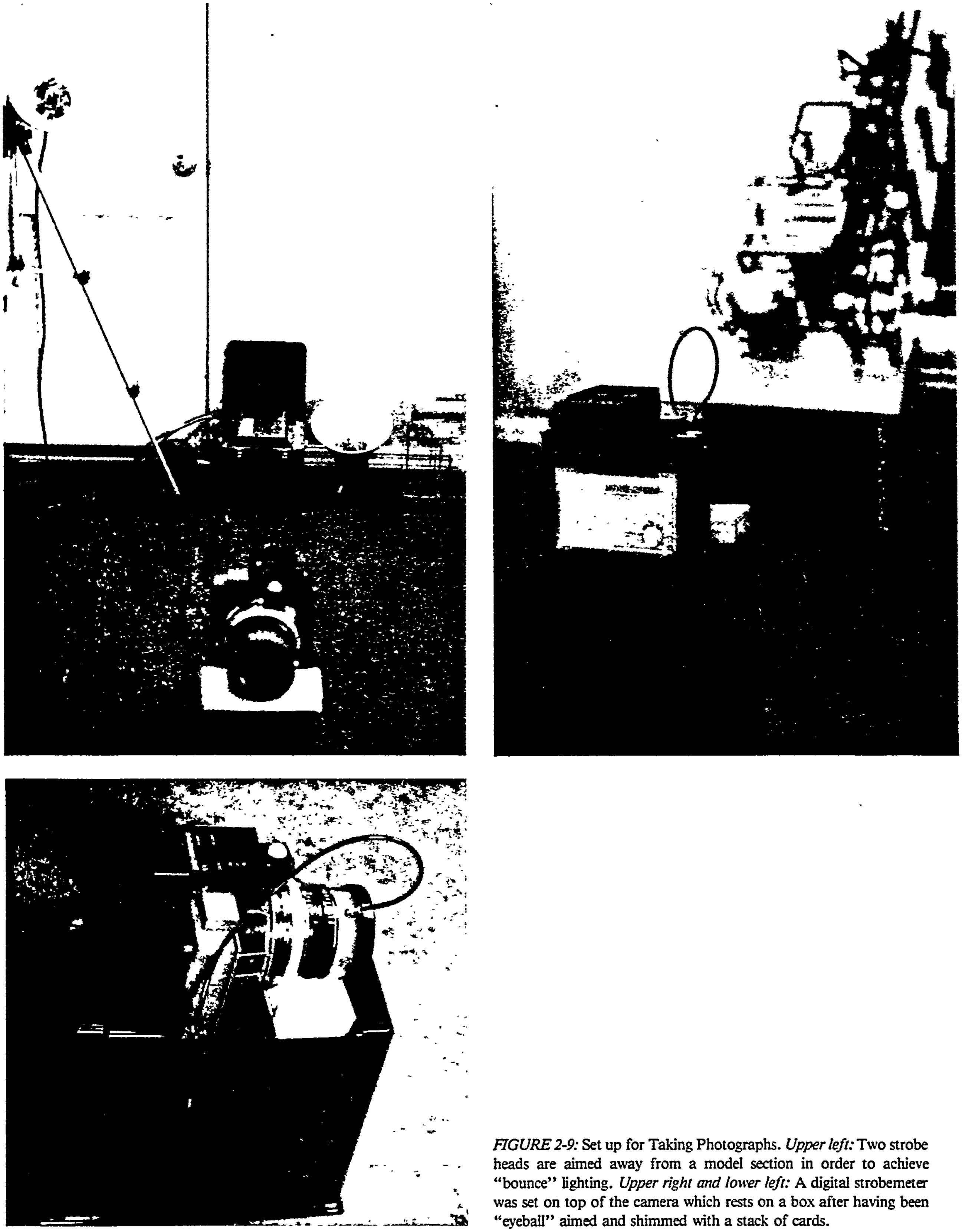


FIGURE 2-9: Set up for Taking Photographs. *Upper left:* Two strobe heads are aimed away from a model section in order to achieve "bounce" lighting. *Upper right and lower left:* A digital strobemeter was set on top of the camera which rests on a box after having been "eyeball" aimed and shimmed with a stack of cards.

2.5.1 *Photo Enlargements*

For familiarization and orientation purposes, the stereodigitizer operator was furnished just one print from each stereopair. An enlargement of just that portion of the negative showing the model section proper was best for this purpose. An 11 x 14-inch size proved to be ideal as it is practical for a photographic laboratory to produce, is easy to handle, and provides a sufficiently large scale for preparing uncongested line tracings of piping.

2.5.2 *Transparent Overlays*

Specific details to be digitized were marked on transparent overlays. A typical overlay and the 11 by 14-inch photo-enlargement from which it was made are shown in Figures 2-10 and 2-11 respectively. Four types of detail were identified:

- control points, i.e., targets defining locations of known ship's coordinates,
- tie-in points, i.e., targets placed to aid in the matching of data digitized from different stereomodels of the same model section, and
- pipe events, e.g., nozzles, valves, couplings, tees, etc.

Colors were used on each overlay to aid the stereodigitizer operator in following a given pipe run. The very simple numbering scheme employed is noteworthy, i.e., one and two digit numbers for points identified by targets and a pipe-run/segment number designation for each straight-line portion of a pipe.

Experience indicated that the overlays are best prepared when the model sections are available for easy reference. If they are not available, frequent reference to color snapshots of the models is nearly as efficient.

2.5.3 *Stereodigitizer Settings*

If a computer-controlled stereoplotter had been employed, such as the one shown in Figure 2-12, setting the position and attitude of one photo of a stereopair relative to the other would have been quickly accomplished by the operator *interacting* with the instrument's computer. However stereodigitizers such as the one used, also illustrated in Figure 2-12, are analog stereoplotters on which encoding and recording devices have been added for three-dimensional digitizing. On this type of instrument the needed relationships are obtainable by time-consuming trial-and-error processes. As a practical matter, precalculation of the settings for each stereopair is a necessity.

The precalculations were made in two steps. First, each negative of a stereopair was measured separately on a *monocomparator*. The measurements simply fixed the photo-locations of a few discrete points (e.g., grid intersections and/or targets on both the model and the wall in the background) which appeared on both negatives. Then, these measurements were computer processed, using a program devised to produce the settings for the specific analog stereoplotter employed.

2.6 *Stereodigitizing*

The analog stereoplotter used was equipped with encoders and a recording device and was connected *on-line* with a minicomputer for processing digital data. Programs were prepared to present certain prompts to the operator on an alpha-numeric input/output terminal. Responses were entered through a keyboard. These entries were automatically supplemented by XYZ coordinates (digitized by the operator while viewing a stereomodel), fed to the minicomputer and stored on discs.

2.6.1 *Digitizing Sequence*

Due to the advance preparations the stereodigitizing work was routine and proceeded rapidly. The following sequence is typical of that employed for each model section:

(a) Load glass-plate negatives in photo carriers of the stereodigitizer.

(b) Manually dial precomputed instrument settings.

(c) Fine tune the settings while visually observing the stereomodel.

(d) Start the prompting program and answer questions such as model-section number and types of detail to be digitized first.

(e) Enter the indentity number of each target via the keyboard, find the point in the stereomodel and press the "record" foot pedal.

(f) Advise the prompting program via the keyboard that pipe segments will be digitized next.

(g) Type in the pipe-run number.

(h) Type in the first segment number.

(i) Digitize points on the pipe segment surface.

(j) Repeat steps (h) and (i) for each of the same pipe run's remaining segments.

(k) Repeat steps (g) through (j) for each of the remaining pipe runs that appears in the stereomodel.

(l) Advise the prompt program that events will be digitized next.

(m) Enter the pipe-run and segment numbers for which events are to be digitized.

(n) Enter the event number to be digitized.

(o) Digitize one or two points on the event as necessary.

(p) Repeat steps (n) and (o) for each of the remaining events on the selected pipe segment that appears in the stereomodel.

(q) Repeat steps (m) through (p) for each of the remaining pipe segments appearing in the stereomodel.

(r) Advise the prompt program that digitizing from the stereomodel is completed.

2.6.2 *Detail Procedures for Pipe Segments*

Experience disclosed that just six points should be digitized for each segment (and repeated within each stereomodel in which the segment appears) in approximate locations as shown in Figure 2-13a. The computer program which best-fits a cylinder to all points digitized on a segment's surface made no rigid assumptions as to the locations of the points, but it did use the digitizing sequences shown in Figure 2-13 as follows:

- points 1 and 2 were used to estimate the pipe-segment diameter, and
- points 1 and 4 were used to estimate the location and orientation of the segment.

Estimates thus obtained were then refined in the cylinder-fitting process. Even when there were obscurations, the approximations for diameter, location and orientation of a segment were usually obtained by wisely selecting and sequencing point locations; see Figure 2-13b.

Digitized points were located reasonably close to bends because the points of real interest are in fact the intersections of the centerlines of the cylinders best-fit to adjacent pipe segments, i.e., the bend-intersection points. Accuracies of the calculated centerlines were better when cylinders were fit to points that were widely separated lengthwise. Theoretically, accuracies would be further enhanced if additional points were digitized. However, the remaining choices for locations, toward mid length of a section, were undesirable. This is because unintentional curvature, common in a modeled pipe segment that is relatively long and small in diameter, invalidates the concept of cylinder fitting.

2.6.3 *Detail Procedures for Pipe Events*

Unlike pipe segments, pipe events were usually sufficiently fixed by digitizing from only one stereomodel rather than all four. Decisions as to which events were to be digitized and in which stereomodels, were best made during the preparation stage. Since surfaces are not fit to pipe events during data processing, digitizing one or two points was generally sufficient to fix each event location and orientation, i.e., there was no need to digitize data from all "sides."

The pertinent data-processing program simply constructed a line in space through the digitized point(s), perpendicular to the previously computed location and orientation of the pipe segment centerline to which the event belonged. For an event with a single digitized point, the location at which the perpendicular strikes the centerline is the centerline location of the pipe event. If two points were digitized for an event, the program would compute their average. Experience indicated that it was best to permit the stereodigitizer operator to decide whether an event should be a "one or two point" event. With this freedom of choice the operator digitized a symmetrical valve simply by using one point on its stem. Asymmetric events were defined as two point events, e.g., one point on each flange of a non-standard check valve.

2.6.4 *Completeness*

The photogrammetric scheme outlined allows four chances to capture data for any pipe segment or event even though it may be partially obscured in all stereomodels. Moreover, there are only preferred, not rigid requirements as to where data should be taken in any one view. Because of this general approach, virtually all piping detail can be dimensioned by the photogrammetric process demonstrated. Even if an occasional detail is not captured, this presents no significant difficulty because provision was made to permit merging manual measurements or presupposed details based upon experience into computer data-files.

2.6.5 *Data Processing*

Many data-processing functions have already been explained in the foregoing because they influence all tasks including those from preparation of a model through stereodigitizing. However, further explanation is needed for full understanding of the logical progression of calculations.

For each model section the data processing steps proceeded in the following order:

(a) By means of a three-dimensional coordinate tranformation program, all digitized information from stereomodel number two was put into the coordinate system of stereomodel number one. Similarly, data from stereomodels three and four were put into the coordinate system of stereomodel number one. This was necessary because each view (stereomodel) of a given model section was digitized in its own arbitrary coordinate system whereas all data from all stereomodels must eventually be in the same coordinate system. Data was transformed from one stereomodel to the coordinate system of another by best fitting the two sets of data at tie-in points common to both sets. This transformation process consisted of two distinct steps. First, in consideration of only the tie-in points, the program determined seven transformation constants (3 shifts, 3 rotations and a scale factor). These, when applied to the second set of data, converted it to the coordinate system of the first set so as to minimize any remaining differences between coordinates of tie-in points in the first set and the transformed coordinates of tie-in points in the second set. Once the seven constants were determined, they were applied to all data in the second set in order to convert them into the coordinate system of the first.

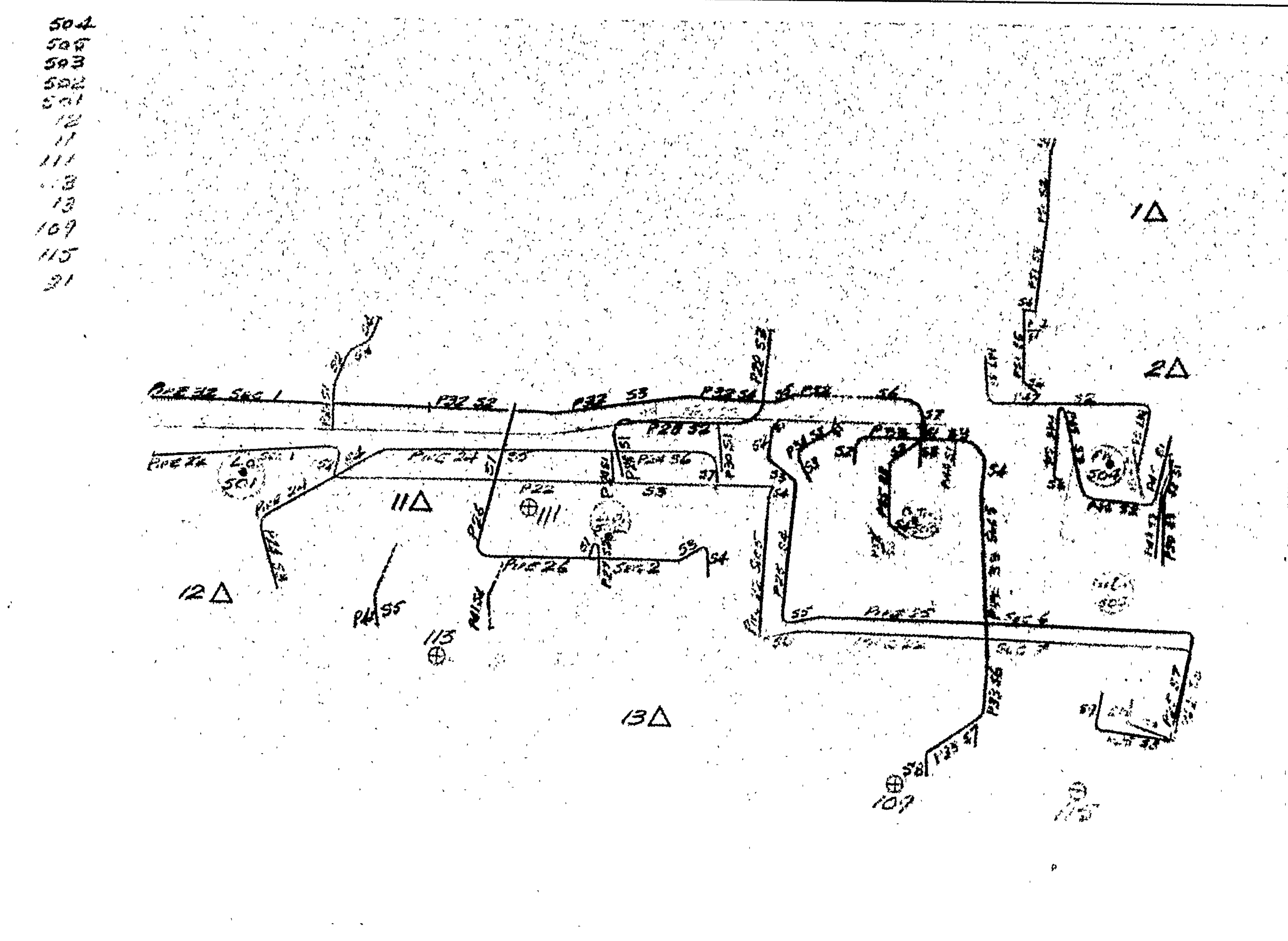


FIGURE 2-10: Typical Overlay for Pipe Segments. It was made from the enlargement shown in Figure 2-11. The notations shown are sufficient for a stereodigitizer operator having only nominal indoctrination in digitizing from models of ships' machinery spaces. Pipe events are annotated on a separate overlay to avoid congestion. They are digitized during a separate pass.

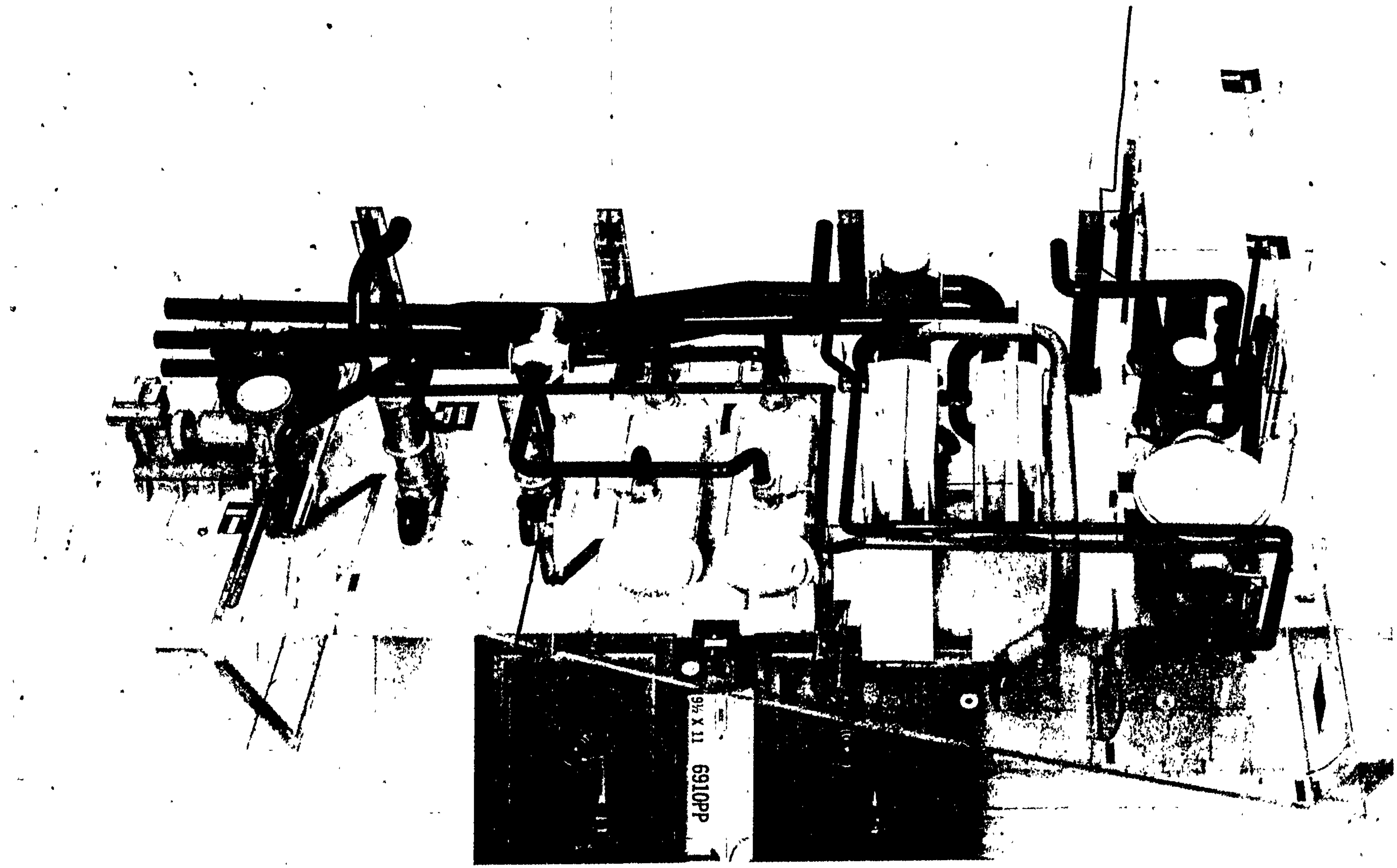


FIGURE 2-11: Enlargement for Stereodigitizing Preparation. This print was used to prepare the overlay shown in Figure 2-10. The model section shown is for the 3rd Deck; see Figures 2-1 and 2-3.

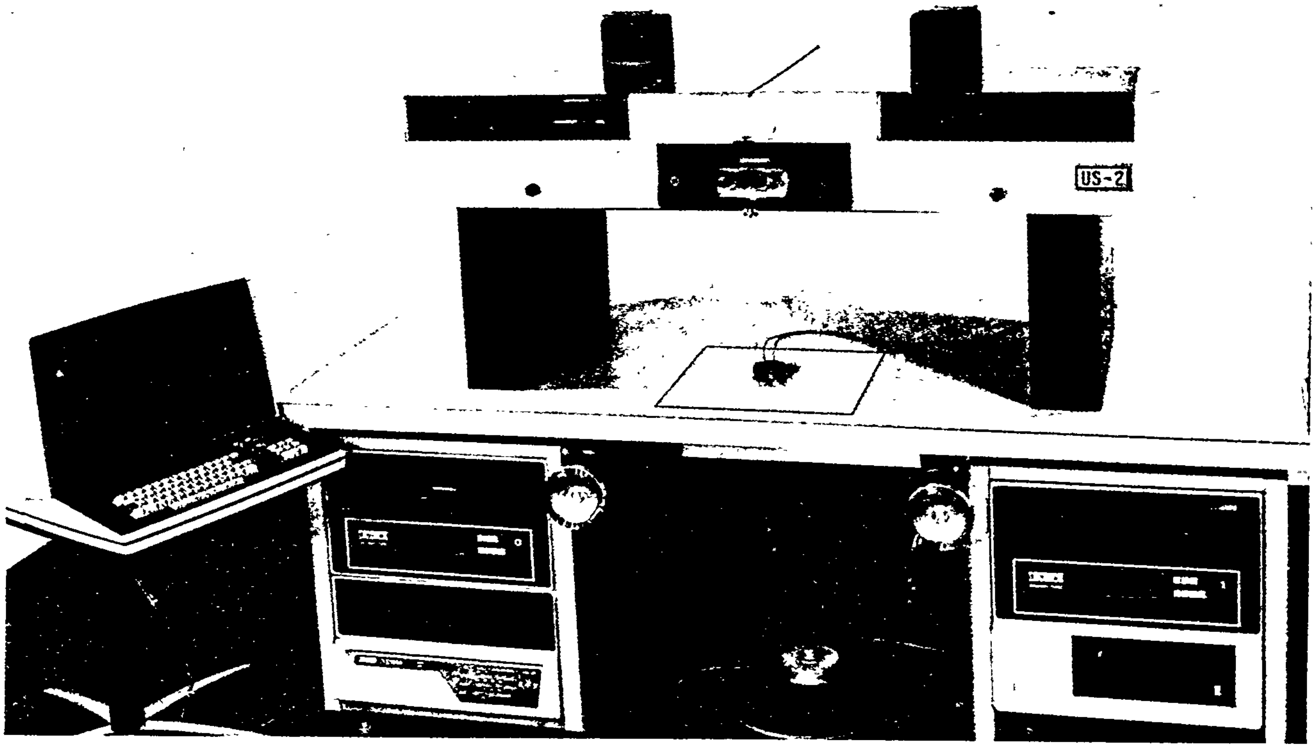


PHOTO COURTESY HELAVA ASSOCIATES, INC.

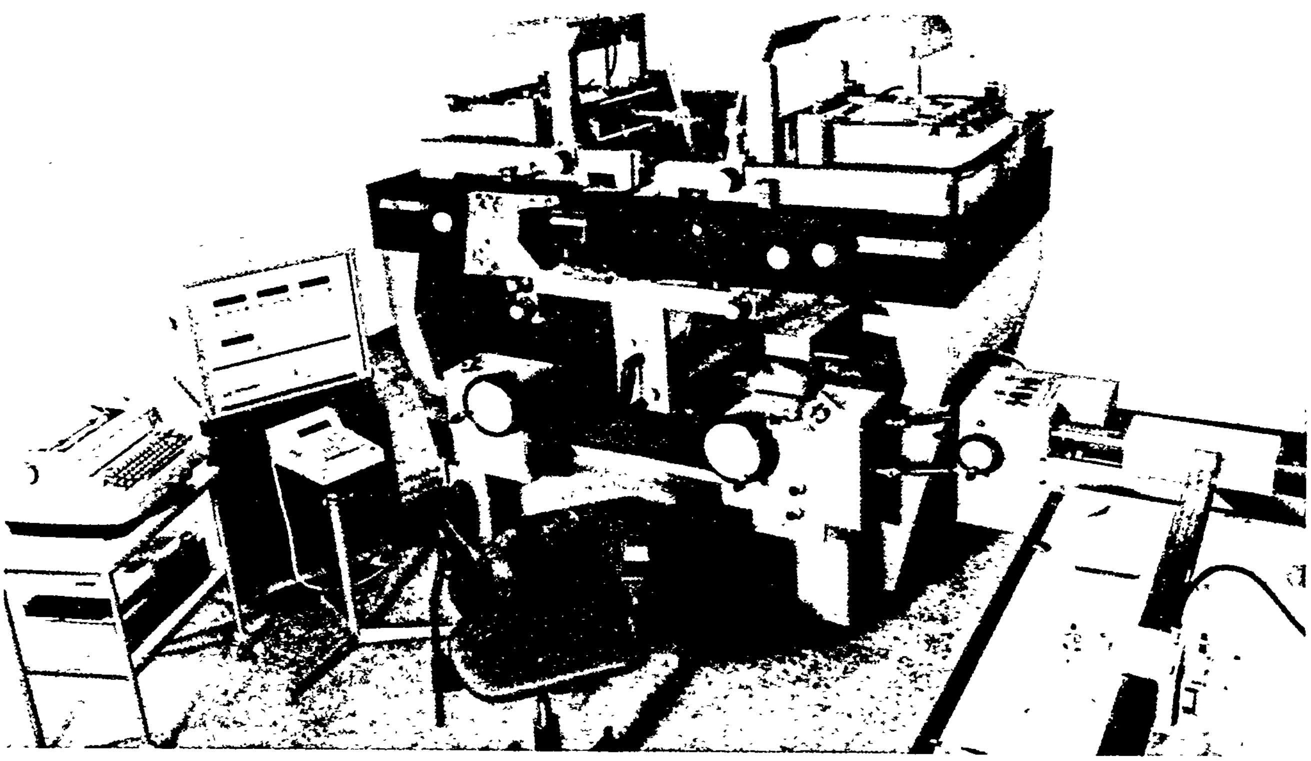


PHOTO COURTESY WILD HEERBRUGG INSTRUMENTS, INC.

FIGURE 2-12: Stereodigitizing Equipment. *Top:* A computer-controlled stereoplotter ($110,000) performs all functions. Its minicomputer numerically solves the problem of orienting one photo of a stereopair relative to the other. *Bottom:* An analog stereoplotter ($190,000) employs precisely machined linkages for aligning a stereopair. In order to perform the same functions as the instrument shown *at top*, it must be supplemented with a minicomputer ($28,000) and a monocomparator ($28,000). All costs shown are estimates (circa 1980). Both instruments can be used to map shapes, i.e., control a drawing machine as shown, *right side bottom*.

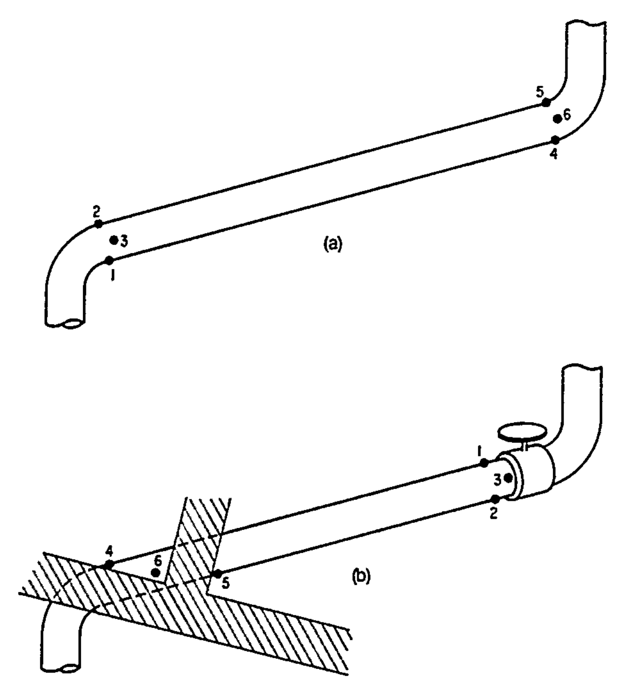


FIGURE 2-13: Locations of Points Digitized on a Pipe Segment. The upper figure shows ideal locations near the ends of a segment. As a practical matter, data are taken wherever a pipe segment is visible such as in the lower figure.

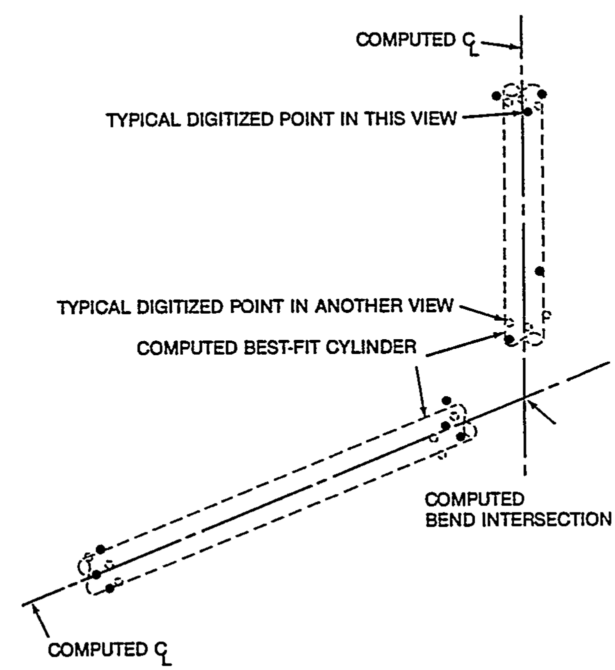


FIGURE 2-14: Bend-Intersection Point. A cylinder is best-fit to digitized points on a pipe segment to find the location and orientation of its centerline. Centerlines of adjacent pipe segments are then extended to find the bend-intersection point. Although the illustration is two dimensional, digitizing and calculations are performed in three dimensional space.

(b) With the same three-dimensional transformation program, all data resulting from step (a) were transformed into the ship's coordinate system. The seven transformation constants were determined by best-fitting coordinates, from step (a), of digitized grid-intersection points to the corresponding known or true ship's coordinates. Once the transformation constants were determined, they were applied to all data from step (a) in order to produce ship's coordinates for every digitize point.

(c) At this stage of data processing, the data even though in a common (the ship's) coordinate system, was very disorganized. Thus, the next data-processing step reordered the data so that all belonging to a given pipe segment were collected together. This was a sorting operation; no calculations were performed.

(d) The collected data for a given pipe segment was then processed through a cylinder-fitting program to determine the location and orientation of the centerline of the cylinder which best-fit all points. That is, the calculation found the radius, centerline location and orientation of that perfect cylindrical surface which minimized the perpendicular departures of all points from the cylindrical surface. The computed centerline locations and orientations for all such pipe segments were stored in a separate file for use in the next two data-processing steps.

(e) Wherever there were two centerlines from adjacent segments (e.g., on each side of a bend), the centerlines were numerically extended in space so as to find their point of intersection. More precisely, each "intersection" was actually the closest approach since it is improbable that two such lines would exactly intersect. The calculated intersection point is the so called bend-intersection point; see Figure 2-14.

(f) In order to determine centerline locations of pipe events, data for a given event after processing through step (b) was matched with centerline data contained in the file resulting from step (d). This was done simply by finding the proper pipe-run/segment number in the centerline data file. Computation of the centerline location of the pipe event then proceeded as described in Part 2.6.3 herein.

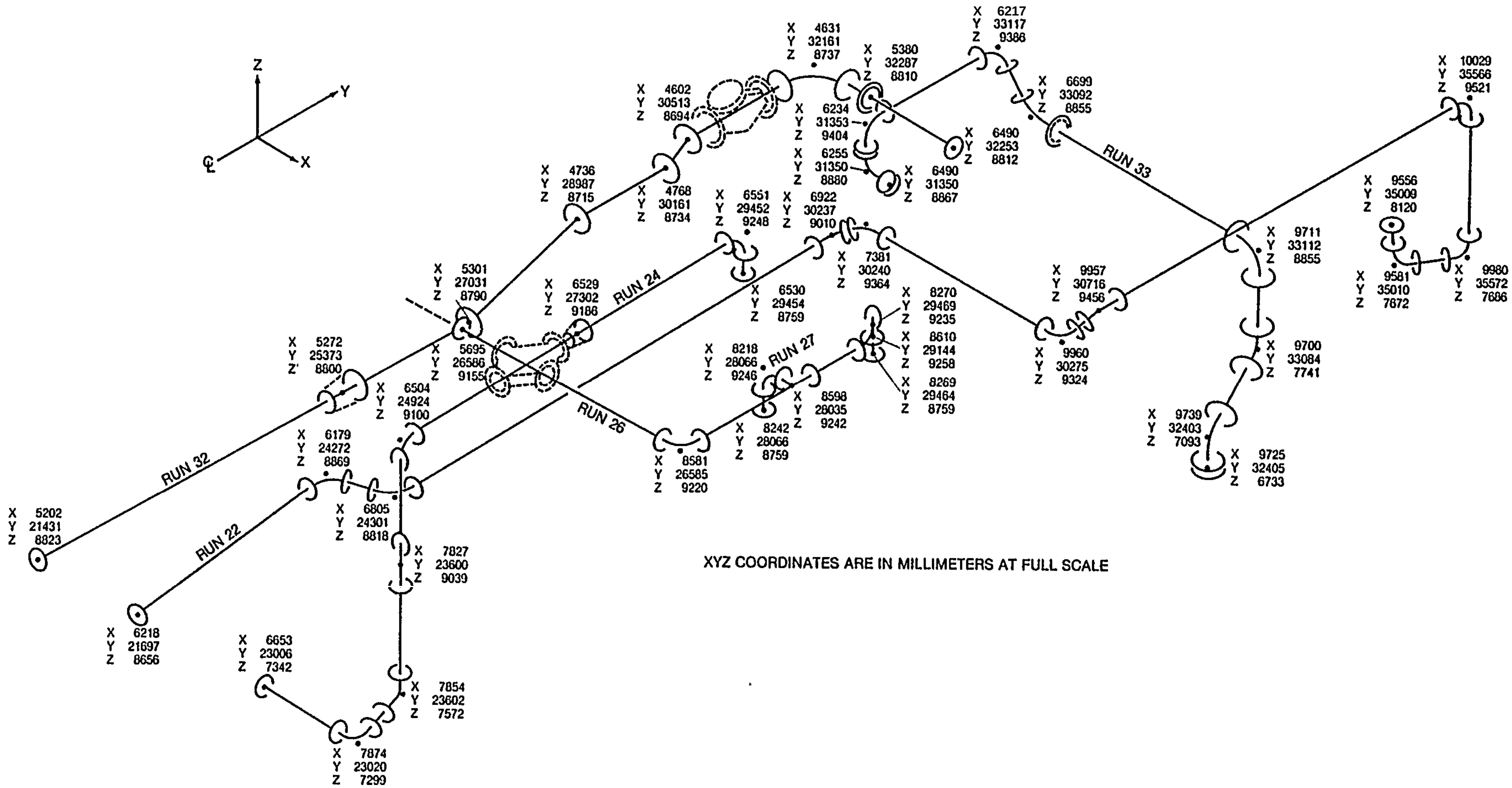


FIGURE 2-15: Geometry of Pipe Runs obtained Photogrammetrically. These sketches were prepared by connecting photogrammetrically determined coordinates of bend--intersection points. The pipe runs sbown corrcspond to those identified in Figures 2-10 and 2-11.

The computed bend-intersection points and centerline locations of pipe events, described in (e) and (f), are the primary end products required of any system for dimensioning from models. They fix pipe-run geometries in formats that can be assimilated by any computer-aided piping design program. Moreover, as they are digital they are consistent with:

- modern methods for preparation of numerical-control fabrication instructions for pipe pieces and related matters (e.g., detail design of pipe supports, holes control, etc.),
- automatically generating material lists, and
- current developments to employ digitized assembly-work instructions.

The need for the latter has recently been expressed by a recognized shipbuilding expert. "After digital computer systems are introduced in this field, the working drawing will be changed to be drawn less geometrically and more numerically. Computer programs accept only numerical data, and since hull structures, machinery, pipes and other items are indicated by numerical sizes, the necessity for geometrical accuracy is comparatively reduced. More manhours are required to produce geometrically accurate drawings, because on geometrical drawings all areas must be accurate, while on numerical drawings only major points must be accurate."[3]

The marriage of design modeling, photogrammetry and computer-aided piping design can productively produce such numerical drawings. As the end products of the photogrammetric phase are only accurately determined major points, even geometric drawings produced by the marriage would be accurate. Renderings are shown in Figure 2-15.

[3]Attributed to K. Ogawa, IHI International Division by C. J. Starkenburg, Avondale Shipyards, Inc., in the presentation "Implementing IHI Technology at Avondale" to the REAPS Technical Symposium 14-16 October 1980, Philadelphia, Pennsylvania.

Analog Stereoplotter—a *stereoplotter* which employes mechanical arms and linkages for setting one photo of a *stereopair* relative to the other and for operating a drafting machine.

Analytical Photogrammetry—the method in which images of specific points of interest within a scene are measured on photographs; these are then computer processed to form a three-dimensional digital model of the scene which, in turn, may be further processed by digital means for final presentation of numerical and/or graphical results.

Attribute—pertinent identifying information, e.g., valve stock number, pipe piece number, material specification, etc.

Camera Station—a location from which a photograph is taken.

Comparator—see monocomparator.

Computer-aided—to be partially assisted by computer action, e.g., the calculation of pipe-bending data from pipe geometry.

Computer-controlled Stereoplotter—a *stereoplotter* which uses a computer to quickly and accurately set one photo of a *stereopair* relative to the other and is equipped with *encoders* and a recording device; it can be used as a *stereodigitizer* or as an *analog stereoplotter.*

Convergence—tilting of the optical axes of adjacent photographs so that the axes tend to intersect rather than remain parallel or diverge.

Design Model—a model whose final form is based largely upon engineering design decisions exercised throughout construction of the model; decisions are guided initially by specifications and system diagrammatics; traditional design at the drafting board is not performed.

Digital—relates to calculation by numerical methods.

Digital Model—a scaled three-dimensional rendition of a scene photographed, generated by computer processing of measurements of images of specific points within the scene or through point-by-point digitizing of an *optical model* in a *stereoplotter*; a digital model consists only of those points in a scene whose images are measured.

Digitize—to record a location by electronic and/or mechanical tracking of the position of a *measuring reticle.*

Digitizer—an instrument for recording relative locations of points; digitizing instruments commonly used in shipyards record only in two dimensions whereas *stereodigitizers* can record in three dimensions.

Encoder—a device for monitoring the position of a reticle along an axis of a *digitizer.*

Event—an occurrence along a run of pipe such as its starting point, ending point and intervening fittings, valves, branches, etc.

Format—a defined order in which data are collected together and presented to a computer program or are output from a computer program.

Geometry (pipe)—an unambiguous and complete numerical description of the locations of pipes and their fittings, etc. in three-dimensional space.

Hardware—tangible equipment such as a computer, camera or digitizer.

Interactive—a dynamic operation wherein a person sits at a terminal and "converses" with a computer; either may convey pre-programmed questions or answers to the other.

Measuring Reticle—a dot or cross-hair within a stereoplotter or monocomparator used to sight upon specific points of interest during digitizing or to trace features for making graphical presentations.

Menu—a chart showing an operator of an interactive digitizing system choices available for symbols, functions, etc.

Minicomputer—a physically small computer primarily intended for *on-line* monitoring and control of equipment.

Model Base—a rigid table upon which a model or portion thereof is constructed.

Monocomparator—a device for measuring relative locations of images of points on a photograph; the instrument consists of an x-axis, a y-axis, a stage upon which the photograph is laid, a measuring reticle and viewing optics; "mono" refers to its being able to measure from only one photo at a time.

Monoscopic—a two-dimensional perception.

Off-line—to perform a function as a second step usually at a point in time removed from an initial action and oftentimes in a different place, e.g., subsequent processing of *bend-intersections* and *events* in a *computer-aided* pipe detailing program from data recorded on discs.

On-line—to perform a function just as soon as it can be executed and usually in the same location at which the function became ready for execution, e.g., computer processing of *digitized* points on pipe surfaces in a model so that only *bend-intersection* points are recorded.

Optical Axis—that line which passes through the optical center of the lens in a camera and is perpendicular to the camera's focal plane.

Optical Model—a three-dimensional rendition of a scene photographed, created in a stereoplotter by projecting light through negatives of a *stereopair;* the separately projected images are viewed with special optics so as to fuse them in order to create a perception of depth.

Reticle—cross hairs or other such means in the eyepiece of an optical instrument.

Orthographic—a pictoral or graphical presentation of an object which is of equal scale over the entire presentation regardless of depth-of-field.

Photogrammetry—the science of extracting reliable two or three dimensional measurements of a scene from one or more photographs of the scene.

Pipe Geometry—an unambiguous and complete numerical description of the locations and orientations of pipe pieces and fittings.

Ray—a pencil of light or a mathematical line between a point on an object and its image on a photograph which passes through the camera lens.

Relative Orientation—the geometrical relationship of one photograph to another when they were taken; expressed mathematically in terms of the angular relation of the optical axes and coordinate locations of the exposure stations.

Segment—a straight-line part of a pipe piece between two bends, two nozzles or a nozzle and a bend.

Signalize—to place an identifying mark such as a target on an object.

Software—computer programs.

Standard Deviation—a statistical measure of the probable accuracy of a number whose value is the result of more than one independent measurement or calculation; a one-standard deviation accuracy figure means that the difference between the measured or computed value and the true value will probably be less than or equal to the standard deviation 67 out of 100 times; as a practical matter, tolerance is equal to 2 to 2.5 times the standard deviation.

Stereodigitizer—an *analog stereoplotter* equipped with encoders and a device for recording digitized data or a *computer-controlled stereoplotter.*

Stereometric—three-dimensional in nature or having the capacity to produce a three-dimensional result.

Stereomodel—a three-dimensional *optical model* formed and observed within a *stereoplotter.*

Stereopair—two photographs of the same scene but taken from slightly different vantage points and with their optical axes nominally parallel to one another.

Stereoplotter—a projection instrument used to create a three-dimensional *optical model* (*stereomodel*) from negatives of a *stereopair.*

Stereoscopic—a three-dimensional perception.

Tag—an adhesive label upon which identifying information is placed and which is attached to a component within a model.

Target—a mark such as a dot or cross to facilitate location of a point made by a measuring instrument.

Terminal—a device through which a user can enter and/or receive information, usually in connection with computer processing.

Triangulation—in *analytical photogrammetry*, the process of *digitally* projecting *rays* from corresponding images of the same point on two or more photographs to their intersection at that point in the scene.

Wire and Disc—a model building technique wherein pipe centerlines are represented with thin wires and pipe diameters are represented by discs attached to the wires; diameters of the discs are true to scale.

APPENDIX B METHODS IN USE, EARLY ATTEMPTS AND PERTINENT LITERATURE ABSTRACTS

Many methods for dimensioning from models have been conceived. Some are being implemented while others have never developed beyond the experimental stage. A review of all such methods discloses that many people throughout the world, particularly in shipbuilding, desire better ways to obtain dimensions from models. Description of current practices and the pertinent history comprise basis for opinion that photogrammetric dimensioning, although it has been tried before, is now the most productive of all known alternatives. This is because of the relatively recent introduction of computers to control and process data from very precise stereoplotters as employed by the huge topographical-survey industry.

1.0 MECHANIZED DIMENSIONING IN PRESENT-DAY USE

1.1 Vickers Shipbuilding, Ltd.; United Kingdom

Vickers Shipbuilding has implemented Computerized Design for Engineering Models (CODEM). The method for transferring a design model, an ideal data base, into a computer features dual-telescope sighting, i.e., optical triangulation, of points of interest.

Locations so obtained are supplemented by design attributes which are entered through a minicomputer's keyboard prior to recording. Eventually all data are processed by a larger computer for generating isometric drawings, fabrication instructions, bills of material, etc. A more complete description is provided in Parts 3.6, 3.9 and 3.15 of this appendix.

1.2 Hitachi Shipbuilding & Engineering Co., Ltd.; Japan

Hitachi Shipbuilding & Engineering employs a slit camera, adapted from the topographical-survey industry, which produces nearly true orthographic negatives. These, through specially developed photo-processing methods, produce blueprint positives of excellent quality; see Figure B-1.

Two-dimensional measurements can be taken directly from a print of a plan view. A third dimension can be realized by manually measuring the model or by reprocessing through the special camera with the model turned on its side.

Significant development work has been performed to interface the Hitachi Zosen Computer-aided Outfitting Management System (HICOMS) with Hitachi perfected design modeling. As the latter features model sections which reflect planning for on-unit, on-block and on-board outfit assembly work, the combination of the two disciplines has great significance for shipbuilders.

Two types of three-dimensional coordinate systems are being developed. One employs ultrasonic emitters and the other utilizes a laser ranging device. Further information is included in Parts 3.4 and 3.11 of this appendix.

1.3 Elomatic Oy; Finland

Elomatic Oy, a design subcontractor, employs a scanning laser for generation of orthoprints; see Figure B-2. Development of the device was as an adjunct to the firm's design modeling practice for machinery spaces. The orthoprints are digitized for input into a computer. More information is provided in Part 3.14 of this appendix.

2.0 MECHANIZED DIMENSIONING ATTEMPTED

2.1 Early Photographic Methods

Photography has been and remains an integral part of all serious model-building programs because photos are extremely useful visual aids. In the early years of design modeling, attempts were made to use photographs as if they were orthographic projections, i.e., some measurements were scaled directly from photographs.

Because an ordinary photo shows a perspective rather than an orthographic view, it does not have a unique scale. While the scale will be constant for all detail in a given plane parallel to the focal plane of the camera, the scale varies for different parallel planes, i.e., for different depths-of-field, hence it is not possible to accurately scale all dimensions directly from an ordinary photo if the object photographed has depth. In order to reduce the effects of variable scale, also referred to as perspective or parallax, some tried very long focal-length cameras. Ultimately, the concept of scaling from ordinary photographs was abandoned.

2.2 Imperial Chemical Industries, United Kingdom

In the early 1960's Richard Farrand, then employed by Imperial Chemical Industries, recognized the potential of photogrammetry to "lift" dimensional information from design models of chemical plants. Farrand conducted a series of ex-

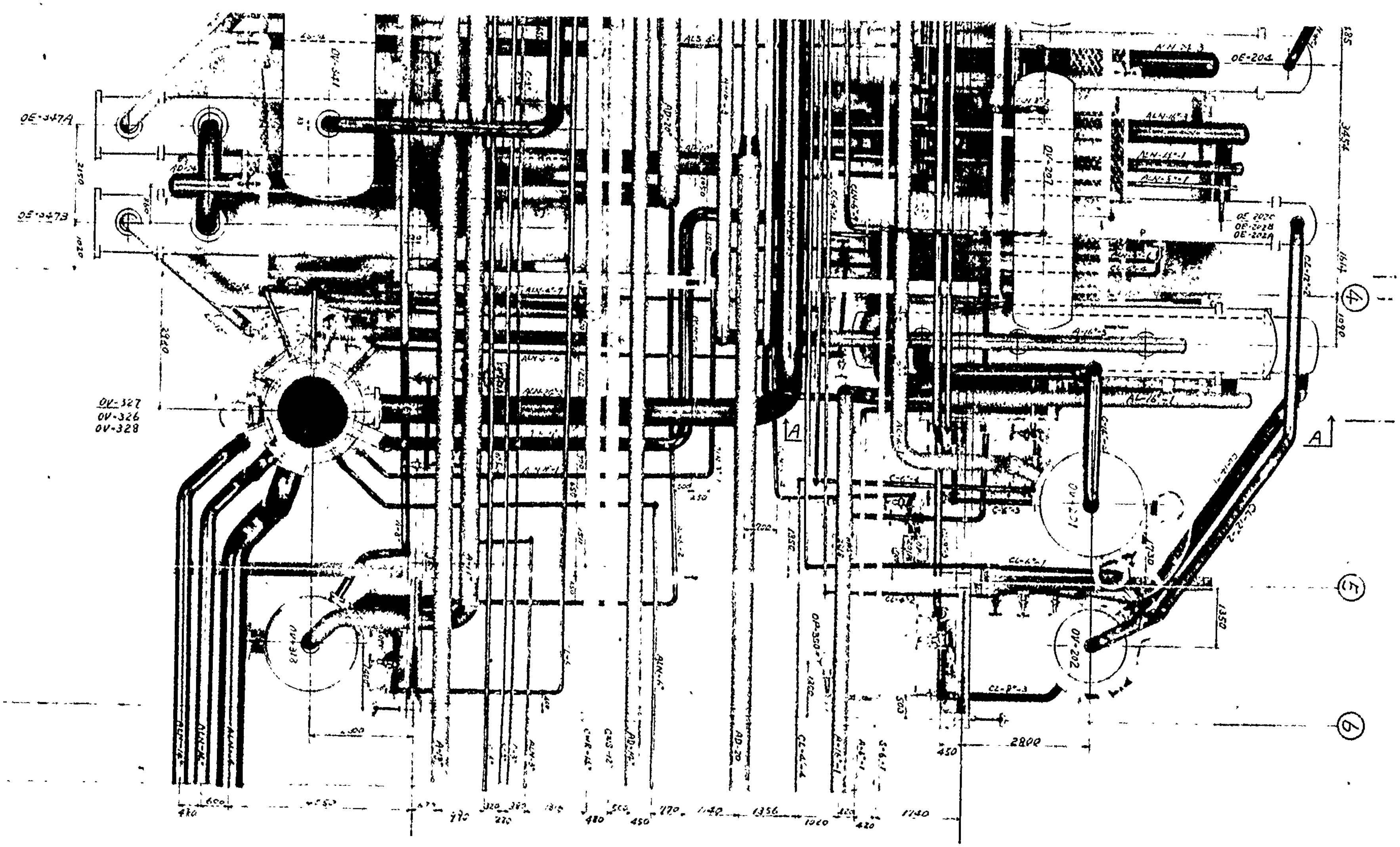


FIGURE B-1: An Orthographic Drawing produced photographically with the "Draft Camera" developed by Hitachi Shipbuilding & Engineer ing Co., Ltd., of Japan.

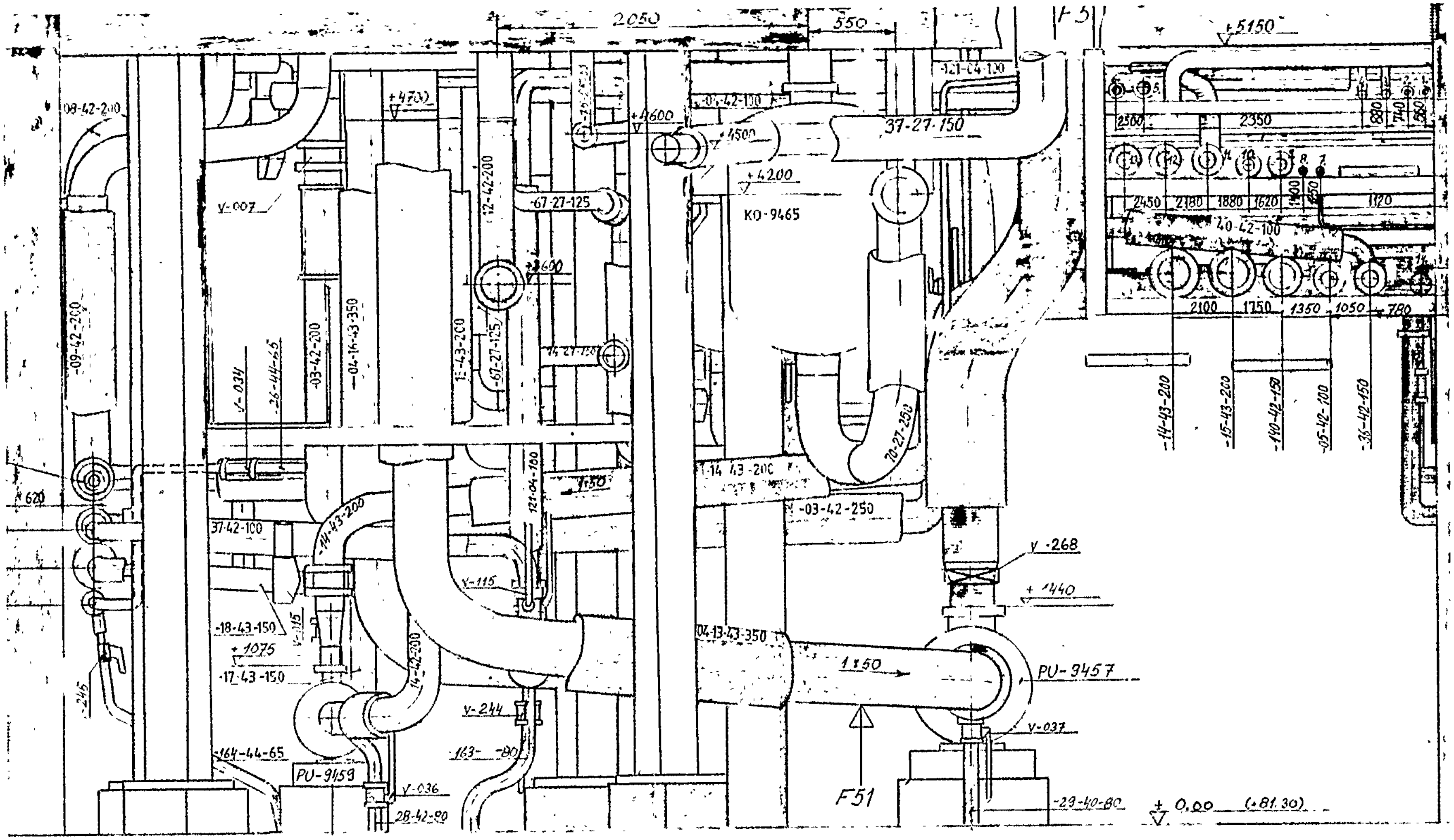


FIGURE B-2: An Orthographic Drawing produced with a scanning laser by a design firm, Elomatic Oy of Finland.

periments which compared manually versus photogrammetrically obtained dimensions from a piping model. The results showed that the photogrammetric method was at least twice as productive and devoid of the numerous errors which characterized the manual measurements.

Based on the favorable outcome, Imperial Chemical commissioned custom-manufacture of a photogrammetric camera and a stereoplotter. In contrast to conventional analog stereoplotters it had two drafting tables. One was dedicated to preparing a plan while the other simultaneously produced an elevation. The drawings were on stable-base material and to an exact scale. Draftsmen later added only necessary annotations. When dimensions were needed by anyone, they were simply scaled from the drawings.

Reportedly, Farrand's system was never put into production because of disinterest by traditionalists. Further description is contained in Part 3.1 of this appendix.

2.3 Utility Data Corporation

In 1972 Utility Data Corporation (UDC) experimented with the use of analytical photogrammetry for determining three-dimensional coordinates of pipe events in a design model of a petrochemical plant loaned by M.W. Kellog Company. William Folchi, a photogrammetrist then employed by UDC, conducted the experiments.

A 1-centimeter grid placed on the model base was a control reference. In order to assure that various features of interest would be exactly identified on different photographs, dotted-line tape, from office-supply stores, was wrapped on the features which were to be located by photogrammetry. A non-photogrammetric camera was employed which required unexpected correction procedures to account for large lens-induced distortions in the imagery of the negatives. Selected points on the 1-centimeter grid and selected dots on the dotted-line tape appearing in the photos were measured on a monocomparator. Points measured on the comparator were "triangulated" and a separate computer program connected points to produce line representations of pipes.

Reportedly, this work was experimental. A commitment to conduct a full investigation was not made because a sufficient market for such services did not appear to exist at that time.

2.4 British Ship Research Association

In the early 1970's the British Ship Research Association (BSRA) investigated an approximate photogrammetric method for digitizing pipe directly from measurements made on two overlapping photographs of a machinery-space model. The digitizing was performed on-line with a minicomputer which was programmed to calculate pipe-bending instructions. A cathode-ray tube displayed an isometric view of a pipe as it was digitized. The only system accuracy reported was $\pm 3\%$ for depth dimensions (i.e. in a direction to and from the observer) which appears to be a one-standard deviation figure rather than a tolerance.

3.0 PERTINENT LITERATURE ABSTRACTS

The abstracts contained herein have been especially prepared in order to place greater emphasis on content pertinent to this project. To some extent, the original authors' expressions are retained. The abstracts are arranged in chronological order.

3.1 "Photogrammetry Applied to Pipe Systems of Chemical Plant" by R. Farrand, Imperial Chemical Industries, Plastics Division, U.K.; The Photogrammetric Record, October 1965.

The design of piping for a chemical plant is created directly in a three-dimensional model which can be separated into sections for access to central areas. Electrical and instrument lines are not shown unless they occupy important space relative to pipes. Pressure vessels and other equipment such as pumps are modeled from their manufacturers' drawings. Their positions, together with general paths of large pipes and pipe galleries are pre-determined in rough-layout models and on flow sheets. Precise routes and details of pipe are then designed as far as possible directly in the model. Pipe centerlines are represented by color-coded wires while their diameters are portrayed by sliding discs. Fittings, such as valves and instruments are represented by symbolic shapes. Intricate and close-fitting details are planned by isometric sketching before being modeled.

Many advantages are attributed to modeling piping design. For example, hundreds of general arrangement drawings are eliminated, the design is more quickly understood and the number of interferences in construction is greatly reduced. Upon completion of the model, however, shapes and dimensions of pipes must still be generated on paper for use by the pipe fabricators and plant erectors. This is normally done by sketching isometrics as the model is put together; general arrangement drawings are then developed from these sketches and by referring back to the model itself. But, difficulties in measuring direct from the model by hand forces the draftsman to estimate many dimensions.

Photogrammetry was seen as an accurate method of extracting and recording accurate dimensional information.

A special camera system and stereoplotter were built by Officine Galileo of Florence, Italy. The camera system featured a pair of identical cameras mounted on a horizontal bar which was supported by vertical columns rising from a base plate. The cameras could be raised or lowered and rotated to point up or down. The separation between cameras was variable and their axes could be adjusted to converge or be parallel. The focus of each camera was variable to accommodate an expected range of distances to a model. Color reversal or black and white "120" roll film was used and each camera's vacuum system held film in a flat position. The cameras were located once for a particular series of photographs. Then, the different model sections were always placed in the same position relative to the cameras.

The stereoplotter is an adaptation from a standard design. Its major unique features are a second set of linkages and second plotting table which permit simultaneous plotting of pipe in both plan and elevation views. As the operator moves the measuring reticle along a given pipe in the perceived optical model, motions corresponding to plan and elevation views are recorded on the separate drawing tables. Typically, the drawing scale is ¾ ″ = 1 ′. Because of a rather short distance between the cameras and the model, an accuracy of ± ¼ ″

(one standard deviation) at the scale of the plant is achieved. Initial results indicate that about 95% of all required detail could be photogrammetrically extracted.

An overlay system is used to convert the undimensioned (but nonetheless "to scale") drawings generated by the stereoplotter to reproducible composite drawings. First, an accurate background is drawn on stable-base film using the plant steelwork drawings and pressure-vessel detail drawings (basically the same drawings used to construct the model skeleton). Then, the stereoplotter-produced pipe sketches are registered to this background using certain reference points on the steelwork or "hard" features such as pressure-vessel nozzles. The pipes are then hand traced onto the background drawing and other data such as pipe numbers and valve references, but not dimensions are annotated. Coordinates of end-points and pipe details such as diameters, valves and other fittings are recorded in tables that supplement the master drawing. Duplicates of the master drawing are made on stable-base film. Each fabricator scales particular dimensions from a copy provided for that purpose.

Investment in the photogrammetric method has been fairly substantial, and in 1965 the method has some appearance of being cumbersome and slow, especially during stereoplotting. Even though the technique has not yet been applied to a complete project, it was responsible for introducing ideas which streamlined the design process.

3.2 *"Computorized Automated System to Produce Piping Design Data for Plant Engineering" by O.I. Brill, Lurgi Mineralotechnik GmbH, presented to the Achema Exhibition, June 1970.*

Data processing programs are a one-time investment whereas preparation of input is a task which reoccurs with every new problem to be computed. Whereas computer technology continues to advance, human performance for data preparation and input tasks essentially remain constant. Because of this, the time required for data preparation is increasing in ever unfavorable proportion relative to the time which a computer requires nowadays for the solution of a problem. This is particularly true for piping design where a large amount of data has to be produced for subsequent preparation of the technical documentation by the computer. But, higher overall efficiency is achieved by making use of newly developed electronic equipment for data production.

In piping work the optimum result can be achieved only by a comprehensive system which integrates all basic variables of planning, design and engineering. Individual elements of such a system must be automated to the greatest practical extent and linked together by the computer. In Lurgi's system data collection is largely centered around the use of design models.

The first stage of piping design involves development of the plant layout and equipment drawings. A rectangular coordinate system is utilized so that once equipment locations are finalized, coordinates and orientations of nozzles can be tabulated and fed to the computer. The computer reserves space within the plant for each piece of equipment and stores their nozzle coordinates as fixed points to which piping must connect.

Preliminary material requirements are determined next. The plant layout plan, the process and instruction (P&I) diagram and the piping specification are used for this purpose. Information such as piping item, size, rating and quantity or length is fed via input sheet or keyboard to a data recorder. However, itemization of piping materials is not performed. Instead, standard components are simply identified by touching its symbol on a digitizer menu. The computer then finds the component in a computer-stored catalog and determines the itemization of materials.

The piping specifications, the P&I diagram and the nozzle coordinates and orientations form the basis for detailed design via scale models which, when completed, show all factors essential for construction of the actual plant. It has been possible to achieve a synthesis between model builder and designer. Preparation of piping studies and sketches is substantially confined to those lines which have special operating conditions (e.g., temperature and pressure) or which are installed in rather congested areas. For the most part piping is directly routed on the model according to specific rules. The model not only fulfills the need of piping engineering but also serves as an aid for field erection and as a tool for training of start-up personnel at an early stage of a project.

Since the model contains all piping design data it was paramount that a method be devised to collect data directly from the model and store them on a recording device. To extract pipe locations from the model a mechanical/optical device was devised for measuring three-dimensional coordinates of pipe events such as bend-intersection points, valve locations, etc. The device consists of two mutually perpendicular rails upon each of which is fitted a traversing telescope. Further, each telescope can move independently in elevation. The two telescopes (which observe only in horizontal planes) are simultaneously aimed upon a point whose location is desired. Since locations of the telescopes are continuously monitored by digitizers attached to the rails, the location of the point of interest is automatically determined.

Only coordinates which vary throughout a pipe run are recorded in this way. Points such as nozzles are not observed since their locations and orientations, which were established at the time of finalizing the equipment layout, are now considered as fixed points not subject to change. By computer processing the measured points are adjusted slightly so as to assure a mathematical closure when a pipe goes from one such fixed point to another.

Computer-generated documents are of two kinds, fabrication drawings and assembly drawings. A fabrication drawing is an elevation of one piping "spool", accompanied by a bill-of-material, with pertinent manufacturing information such as item specification, size, wall thickness, flange specification, rating and flange facing. Component weights and the total weight of the spool are included. A cost sheet organized in order of the bill-of-material is also produced.

The assembly drawing shows a pipe line in isometric and coordinates of all pipe events including locations of field welds. The associated bill-of-material and cost sheet covers only materials needed for assembly.

The mechanical/optical digitizing system for extracting data from models has been in production since 1969. Some 12,000 isometrics with bills-of-material have been produced for 15 different plants such as petroleum refineries, petrochemical plants and synthetic fiber plants. Three persons are needed to operate the system and a fourth serves as an overall coordinator and supervises communication with the computer. 100 isometrics can be produced in a 40-hour work week. Compared to a totally manual effort, only 20-30% of the working time is required when the mechanized system is employed. Overall savings in costs amount to 50%.

3.3 "Photogrammetry as an Aid to Manufacture of Ship Piping", British Ship Research Association Report NS 306 by W.G. Smith, 1971.

The conventional method of generating pipe manufacturing data through preparation of arrangement drawings and sketching of pipes at the ship is considered unsatisfactory. This attitude has developed with the evolution of large shipbuilding groups, centralization of drawing offices and the tendency for increasing physical separation of these offices from the pipe shop and the ship itself. Moreover, computer based management systems being introduced into shipbuilding require, for maximum effectiveness, early availability of operational data. The traditional pipe sketch is not suitable for any of the present-day conditions described.

Because shipboard piping systems are becoming increasingly complex, some yards, in the interest of productivity, have turned to design modeling to assist pipework design. Design modeling also allows early availability of data for use in computer-based management systems. But, the method has also introduced problems in lifting dimensional data needed for the manufacture of piping systems. To present, this has been performed by manual measurement with a rule, followed by the preparation of isometric sketches and pipe-arrangement drawings. This process is not entirely satisfactory owing to limited access for measurements, duplication of data inherent in the model and as portrayed in arrangement drawings and lack of data in a form ready for computer processing.

Photogrammetric measurement provides a more satisfactory solution; its principal advantage being that it is virtually non-contacting. The specific photogrammetric technique adopted for study is described as comparative photogrammetry. Important features of this particular method are that it is not necessary to know the focal length of the camera lens nor the distance between cameras; hence, a relatively inexpensive camera may be used. Also, measurement of the photographs may be performed with inexpensive equipment. While this method is considerably less precise than more rigorous photogrammetric methods, its experimentally determined accuracy of about ±3% is considered adequate.[1] The researchers estimated that over 80% of an engine room's pipes can be measured by photogrammetry. Also, due to inaccuracies in a model, photogrammetric measurement and the actual fabrication and assembly work, some sketching will always be required at the ship for closing lengths and "made-to-place" pipe pieces.

A single camera is mounted upon a horizontal bar which in turn is supported by a pair of vertical columns rising from a base. For aiming purposes the camera may be moved along the horizontal bar and the bar itself may be moved along the vertical columns. Care is taken to align the focal plane of the camera parallel to a vertical plane containing the horizontal bar. The camera system is aligned with the model such that the horizontal bar is parallel to the horizontal datum of the model and that the vertical columns are parallel to its vertical datum.

One scale is placed on the model in the foreground and one is placed in the background. Also, a grid is drawn on the model base or, alternately, special markers are placed on the model to aid in subsequent location of the optical centerlines of the photographs. A series of extensively overlapping views are then photographed across the front of the model.

Measurement of the photographs may be performed with a steel rule on a Farrand Overlap Comparator or on a digitizing table. Enlargements of the original photographs are first scribed with special reference lines to locate the optical centerlines of the pictures. Two photographs are then taped side-by-side on the digitizing table, usually with the optical axes of the pictures aligned with an axis of the digitizing table. Measurements are then made on both photographs to their optical axes, to both ends of both scales and to points of interest on pipes. These measurements which are only X-coordinates are recorded on paper tape for subsequent processing through an elementary computer program which, in its present form can produce only the depths of the pipes from the datum surface parallel to the focal plane of the camera. The process can be extended to incorporate Y coordinates which would permit calculation of heights and lengths.

Actual experiments entailed a series of photographs of a $\frac{1}{10}$ scale wire-and-disc model of the engine room of a dredger; the model being split along its longitudinal centerline. Two different cameras were selected primarily for their ready availability but were not entirely satisfactory because their twin-reflex characteristics presented aiming difficulties at the short ranges involved, about 1 meter. Black and white films were used for both the original and enlarged photographs inasmuch as the piping was not color-coded.

A first set of experimental pictures were measured both on the Farrand Overlap Comparator and on a digitizing table. A number of pipe depths were calculated from both sets of measurements and compared to the known depths. For the two methods of measurement respectively, mean differences amounted to 6.3 inches and 2.4 inches whereas the maximum errors were 44.9 inches and 10.6 inches at the full scale of the ship.

However, a second set of pictures, taken with greater care in aligning the camera system with the model and measured on the digitizing table, produced results at least twice as good.

The researchers presented a number of conclusions. Accuracy would be best improved by refinement of the measur-

[1]This is believed to be a one-standard deviation figure (not a tolerance).

ing system rather than substituting expensive cameras. Great care should be exercised in locating the optical centerline on each photograph. Consideration should be given to a means (e.g., color-coded wires) to aid identification of pipe systems. Further investigation is required to determine how photogrammetry can be interlinked to other production-information systems. Pre-sketching of pipes by photogrammetry or any other method should account for an estimated 80% of the pipe pieces shown on the model. The entire procedure of comparative photogrammetry requires very little training for its implementation.

3.4 *"Prospects of Engine Room Outfitting Design by Scale Model Combined With Computer-aided Outfitting Management System" by Yukio Tomita, Hitachi Shipbuilding and Engineering Company, Ltd., presented to the IV International Symposium on Ship Automation, Genova, Italy, November 1974.*

The first portion of this paper discusses the Hitachi Zosen Computer-aided Outfitting Management System (HICOMS) whereas the latter portion treats the technological development of design modeling and efforts underway to interface design modeling to the HICOMS system.

Up until the last few years, machinery space design was handled through traditional arrangement and composite drawings reflecting design concepts of several highly skilled engineers each having over ten years experience. Typically, numerous trials and errors consumed several months and resulting drawings were difficult for third parties to understand and unexpected difficulties often occurred at the production and outfitting stages. These drawbacks of the traditional system plus an anticipated decline in the number of highly skilled design engineers prompted Hitachi to investigate alternative methods of design. Standardization and computerization of the design process was not seen as a viable alternative. A vast amount of information (particularly hull data) must be handled and considered continuously throughout the design effort, with a wide variation as to which information is given greater priorities. Because of this inherent requirement for a high degree of creativity in the design of machinery spaces, design modeling was seen as a practical effective alternate to traditional design practices.

Hitachi's first design model was of a 36,000 shp steam-turbine powered machinery plant for a 280,000 DWT tanker. The 1:10 scale model was commissioned by the owner to prove operability and maintainability as a complement to the less than ideal practice of drawing approval. Hitachi seized this opportunity to perform actual outfitting design directly on the model. Subsequent to this experience outfitting of four other machinery spaces has been designed in the same way, including that for a 45,000 shp plant of a 400,000 DWT tanker.

Now that design modeling is perfected, efforts are now directed toward integrating the process with HICOMS. (Presently there is an undesirable amount of manual intervention required to transmit information from the model to HICOMS.) Goals of the integration development are:

- mechanization of the extraction of dimensional information from the model
- automation of dimensional-data adjustment to eliminate small numerical mismatches along pipe runs, to force exact parallelism among pipes where that is intended, to account for exact dimensions of standard parts, to create exact bend angles such as 90°, etc.
- automation of pipe detailing
- computer production of fitting-out drawings
- extraction of qualitative information from the model for the fitting-out work
- production of outfitting and management information by HICOMS

For extraction of dimensional data from the model, two types of "three-dimensional coordinate analyzers" are under development by Hitachi under subsidy from the Japan Ship's Machinery Development Association. The first device employs ultra-sonic emitters and receivers at known locations. The end of a measuring rod containing two oscillators is touched upon any point of the model. XYZ locations of the two oscillators are triangulated by a mini-computer using output data from the transmitters and data gathered by the receivers. This establishes the direction of the measuring rod in space. Then, by knowing a distance from an oscillator to the touching point of the rod, the XYZ location of the point touched is found.

The second device, as conceived, employs an optical sight and a laser ranger. The optical sight moves in a fixed plane and its location in this plane is continuously monitored as are its pitch and yaw when it is sighted upon a point on the model. These data along with the laser-measured distance to the point are processed by a minicomputer to yield the XYZ location of the point sighted.

3.5 *"Pipe Production Information: A Computer-Aided Method," The British Ship Research Association Report NS396 by B. Dodd and J. B. Jack, 1974.*

A major disadvantage of current practices for developing pipe manufacturing data is that the pipe shop does not receive the data with sufficient lead time so as to allow planning and batching of pipes for the bending machines. Moreover, the machine operator normally works from pipe sketches and, in some instances, may even prepare a small wire model of a pipe or engage in a lofting process on the plumbing shop floor. The operator's productivity could be increased if he were provided directly with a concise clear list of instructions for each pipe, from which he could work directly. Also, any system which can reduce the number of tried-in-place pipes would also increase productivity.

When design modeling is employed pipe dimensions and angles are normally lifted manually from the model by a draftsman. A previous study documented in the British Ship Research Report NS 306 "Photogrammetry as an Aid to Manufacture of Ship Piping," demonstrated the potential for photogrammetric dimensioning of design models. Since that report, continued research produced computer programs which can convert digitized photogrammetric data into spatial coordinates defining a pipe's shape.

Isometrics can be plotted, but the process is cumbersome in that it is entirely an "off-line" procedure; i.e., computer processing and drafting are entirely separate from photogrammetric digitizing. Independently, another computer program was developed to generate pipe-bending data from coordinates defining a pipe's shape. And, also separately, Imperial College was in the process of developing a computer aided drafting system.

This BSRA report describes efforts to combine all of the above developments so that pipe-bending instructions could be produced, on-line, directly from photographs of a design model. The hardware system for digitizing the photographs and producing the required bending data consists of a digitizing table, a PDP-8 minicomputer with 8K words of memory, a teletype for program-instruction input and printed output and a cathode-ray tube (CRT) for display of isometrics. To start up the system it is first necessary to input certain definition parameters via the teletype and to digitize certain reference points on the photographs which are taped to the digitizing table. The minicomputer immediately performs an accuracy test on these data and signals the operator (via the teletype) whether the data are acceptable. Once this stage is completed successfully, a given pipe of interest is identified through the use of a "menu" on the digitizing table and then digitized on the photographs. As the digitizing proceeds, the path of digitizing is displayed on a CRT in isometric view as a visual check. The CRT tube may be photographed if it is desired to use the isometric display as a replacement for the pipe sketch. Once the digitizing is completed, the pipe-bending program is invoked and calculated bending data are printed out on the teletype along with messages (if any) regarding improper floor clearance, clamping length and radii which are too small.

For a single pair of photographs about one minute is required to digitize the set-up data and another minute is required for each pipe to be digitized. Calculation of bending data is about one second per pipe but the printout is at a lesser rate owing to the slow speed of the teletype. However, the teletype is easily replaced by a faster device. Hence, most pipes within a typical model section can be digitized and corresponding bending instructions generated in an hour or two. However, the present system is not considered complete inasmuch as there is no capability for detailing pipes. This will be considered in the next stage of development. It is also suggested that consideration be given to utilizing this system during the design-modeling process to assure that practical designs are developed utilizing standard shapes, lengths, angles, etc.

The balance of this report gives finer details on the computer program concepts for converting digitized data to pipe coordinates and then translating these to bending instructions. Flowcharts of the programs and a typical output are given in appendices.

3.6 *"A Systems Approach to Total Ships Outfitting" by P. Bech, paper presented to Seascape '76 Conference on Developments in Shipboard Outfitting, University of Newcastle upon Tyne, April 1976.*

This paper addresses increased productivity resulting from design with due regard to production methods and facilities, to planning and to production preparation. In this context the use of design models at Odense Steel Shipyard is described along with computer systems for transforming design data into production information. The paper also deals with production flow of prefabs, sub-units and super-units. Also, the economics of integrated methods used at Odense are discussed. Finally, observations are made as to how far a designer should go to ease the production burden.

Outfitting system diagrams are developed from a general arrangement and the specification describing the function of the vessel. This leads to basic decisions on major machinery components. Next, design of the main layout of the engine room is accomplished with a 1:40 scale model. A model at this stage of design allows quicker and better decisions while providing a ready mechanism by which production personnel and owner's representatives may review the arrangement of major components, major auxiliaries, main ventilation, access during the building phase, securing of space for pipe withdrawal and exchange of major components and, finally, functioning of the engine room once the vessel is placed into service. The model is also used to decide upon subdivision of the engine room into production blocks of suitable size (up to 575 tons at Odense).

Detailed design work is carried out on a model of 1:15 scale. All piping down to 1½" is laid out, complete with positioning of valves, cable trays, lighting fixtures and all other engine room equipment. The model typically requires ten people working on it continuously over a period of six months. At Odense the hull or structural model is obtained via subcontract; Odense's model workshop concentrates only on machinery items and piping arrangements.

As with the 1:40 scale model, frequent decision making meetings are held around the model to decide upon the best possible arrangements from the shipyard's and the customer's point of view. For examples, positioning of maneuvering valves, piping details amenable to easy overhaul, temporary supports in the blocks, decisions regarding sub-units, etc. It is also seen that machinery components are located free of block divisions.

Initially design modeling was intended primarily to achieve better layouts of engine rooms. This was considered enough justification for the modeling approach even though the advantages would be difficult to count in a monetary sense. Once implemented, however, the model-building program led to other development pertaining to creation of production information.

The Odense "pipe sketching system" starts at the model where coordinates of bends, joints, flanges and other piping armatures are "lifted" from the model and used for a handmade isometric sketch. A basic angle calculation program is used to determine angles in bends. Where possible, these initial angles are modified to be standard values. Corrected data along with material specification/dimensions, prefab block numbers, fabrication operation schedule and assembly block numbers are fed into a computer data base. Output from this consists of:

- symbolic pipe sketches
- pipe bending instructions
- piece work rate for each operation
- pipe "batching" work orders
- planning data from piece work rates and work orders, and
- pipe mounting lists

In its present form, the pipe sketching system requires a long period between design and production owing to the step-by-step manual input to the computer with attendant data correction and resubmission. In the past this has not been a problem where order stock in the yard was large. But in the present shipbuilding market, Odense has been forced to change its product program and such time-consuming methods can no longer be tolerated. Accordingly, the pipe sketching system has been streamlined by addition of a visual display unit placed next to the model itself. Coordinates lifted from the model are entered at the display unit and immediately processed to verify the input for closure, adjust angles of bends, produce an isometric pipe sketch and list material data, armature lists, etc. Hard copy of the display can also be made at the unit. All correct results are then transferred to the data base for subsequent use in production preparation and in production. Obviously this streamlining of the system will save man hours in design but more importantly, it drastically shortens calendar time between design and production of fabrication and planning documents. Odense's experience to date indicates that a little more than two ships of the 45,000 to 70,000-dwt class can be handled per year with a single visual display unit. Development is continuing to extend use of the system to electrical equipment, cabling, HVAC, etc.

The remainder of this article describes other computer aided outfitting systems in use at Odense, but these are not pertinent to this project. However, a discussion by D.E. Gilbert of Vickers Shipbuilding Limited is of particular significance. He stated that there are many advantages to design models but the key to success is dimensional accuracy. Vicker's experience indicates that this accuracy is lost when model scales smaller than 1:10 are employed. In their models the structural portion is built to a tolerance of +0, -2 mm per 1000 mm while equipment and pipe work are modeled to "measurable accuracy." Because the model is an interdisciplinary design tool, it is the focal point for all drawing offices. This results in faster generation of production information.

There are few disadvantages of design models. Perhaps the most serious is the cost involved. It can be argued that this cost is justified if the ship is complex or if a series building program is involved. In the case of a "one-off" commercial ship, it may only be economical to model particularly congested areas. Another criticism sometimes leveled is that ergonomical problems are not readily appreciated. However, Vickers has successfully used models to demonstrate maintenance and operating operations.

It is debatable whether the two-model approach used by Odense has any advantage over the more conventional single model system. Certainly the detailed design model can be also used to establish the equipment arrangement. At Vickers, piping is represented true-to-scale rather than by wire and disc.

Vickers has developed a system called "CODEM" (Computerized Design from Engineering Models) which is unique in that it is used to extract information directly from a three dimensional model, thus providing a real savings in time and money. Prior to developing the system, it was very necessary to completely standardize pipework documentation in the form of isometric drawings, parts lists, numerical information and single-line arrangement drawings. Once this common methodology was established, the computer was introduced to replace much of the manual effort required to produce such documentation.

The first stage of CODEM is the design model itself which is made very accurately in sections not larger than about 6x6x6 feet. All machinery, piping, electrical equipment, ventilation ducting, structural items, walkways, control panels, etc., are accurately modeled. When the model sections are completed, they are placed one at a time on a fixed table of a three-dimensional telescopic unit. This unit consists of two telescopes which travel on rails constructed at right angle to one another. Both telescopes can also move in a vertical direction independent of one another. Locations of the telescopes are continuously encoded so that their locations relative to the model are always known, or at least can be computed by the on-line minicomputer to which the telescopic unit is connected. To enter data into the computer for a given piping system, an operator at a typewriter-like keyboard/visual display unit manually keys in a coded description of the pipe. When geometric data are needed the operator "instructs" the computer to accept the current locations of the two telescopes. Data entered in this way are stored on magnetic tape. This tape is later fed to a main computer in which details of all pipe components are stored. As the magnetic tape is read by the computer, each general description of a pipe element is matched with the appropriate details. Calculations for length, weight, quantities, etc., are performed and another magnetic tape is generated for automated plotting of isometric drawings. These drawings are fully dimensioned and labeled with all information necessary to manufacture the pipes, bending instructions included. Parts lists and summary lists are also generated.

3.7 *"Photogrammetry in Shipbuilding" July 1976 by john f. kenefick Photogrammetric Consultant, Inc. for the National Shipbuilding Research Program.*

A survey of potential applications of photogrammetry in shipbuilding, ranging from design to post-delivery, is supported by detailed accounts of four actual demonstration projects. Appendices provide a glossary of photogrammetric terms, a layman's explanation of photogrammetry and exhaustive compilations of pertinent literature and sources of photogrammetric hardware and services.

One of the demonstrated applications established the technical feasibility for generating dimensioned arrangement drawings from photographs of a design model. A series of stereopairs of photographs, viewing from inboard to outboard, were taken of a portion of the starboard side of ¾" = 1' machinery-space model. A single-frame glass-plate camera was used to obtain all photographs. Within the region photographed, a ⅜" = 1' elevation view of the main-steam piping was produced on a stereoplotter. Fixed machinery was shown in phantom. This drawing was then placed upon a digitizing board to obtain dimensions from deckheads and bulkheads to pipe centerlines. A check of 20 such dimensions against design values showed average and maximum differences of 1¼ inch and 2⅝ inch at the scale of the ship. These values, however, included error in the model itself since the model was built from a design produced first on paper. In design modeling, this source of error would not be present. While the graphical presentation of piping served the immedate purpose of the demonstration, it was concluded that a digital "take off" from the photographs is preferred in order to be compatible with computer-aided piping design systems.

3.8 "Advanced Pipe Technology; Detailed Final Report—December, 1976," by Newport News Shipbuilding, Newport News, Virginia for the National Shipbuilding Research Program.

This report documents domestic and foreign state-of-the-art technology for piping design, fabrication and assembly. Particular functions addressed are contract definition, special material identification, diagrams, arrangements, pipe details, hanger design, operating-gear design, scheduling, and the preparation and revision of technical documentation.

Very little difference was found in piping design practices employed by surveyed domestic design agents and shipbuilders. Foreign shipbuilders place greater emphasis on accuracy and detail. Both orthographic and isometric drawings are discussed without a stated preference. Regardless of the type, minimum requirements for each such drawing are:

- simplified structural background,
- display of approximate arrangement and configuration of piping runs, pipe sizes, special valves, special fittings, equipment and tanks,
- symbol list,
- title block, and
- lists of materials, e.g., pipes, special valves, special fittings, equipment, tanks and pumps.

Pre-printed structural backgrounds and computer programs for pipe sizing and related calculations are the most significant cost-effective methods utilized by the surveyed domestic design agents and shipyards. Also, in the absence of standard ship designs, computer-generated diagrams, as developed by Italcantieri of Italy, offer significant cost savings.

Three-view orthographic drawings are generally used by domestic design agents and shipbuilders. Isometrics, used by one domestic shipbuilder and relatively common abroad, aid assembly work.

Various techniques utilized by surveyed design agents and shipyards for interference control include:

- designer liaison,
- space composites,
- space composite based on "piping conduits," i.e., reserved zones,
- overlays,
- computer-aided detection, and
- models.

Only three surveyed domestic shipyards use models for interference control for just special isolated areas. One surveyed foreign shipyard, Odense of Denmark, uses models exclusively for design of machinery and distributive systems arrangements. Isometrics, manually prepared from the model, are computer-processed to produce symbolic pipe details, fabrication instructions and material lists.

Isometric presentations appear to offer significant advantages for certain applications. Moreover, the development of such sketches directly from design models is significant in that the combined process eliminates much of the duplicative effort seen in domestic model-building/design-engineering practices.

Computer-aided pipe detail programs is one of the mos significant advancements in piping technology. In addition, i is the first logical step toward integrated piping design manufacturing/assembly systems. Currently computer-aide systems facilitate cost-effective pipe fabrication but they hav not yet facilitated cost-effective design methods.

Discussions are included about various totally integrated systems under development in a number of domestic and foreign shipyards. Typically, these integrated systems are based on design via interactive graphics or upon digitizing designs first prepared upon paper. However, a unique variation from these concepts is the Odense computer-aided design-model system.

At Odense, the use of models originated as a tool to study new ship designs and to aid marketing of these designs. However, models were ultimately incorporated as a part of the regular design process because of their numerous advantages:

- portrayal of complex arrangements without the need for skilled designers,
- ready realization of best arrangement of machinery and piping, thereby optimizing the layout of piping, ventilation, wireways and gratings,
- handling and overall space requirements are easily determined and staging requirements are minimized,
- interferences are easily detected and virtually eliminated at the design stage, and
- models serve as common basis of communication between the owners, regulatory bodies and the shipbuilder.

With the adoption of design modeling, the design department abandoned the traditional methods of preparing arrangement drawings, composites and pipe details. Under the new scheme of operation using design models nearly 90% of a ship may be pre-outfitted as compared to 15% with the old method.

A portion of the design department has been made into a model shop in order to facilitate model construction. Of 81 persons involved in machinery outfitting design, 13 to 16 of these are responsible for construction of engine-room models. Fabrication of a model is by designers who are also experienced in model building. They work directly from machinery arrangement diagrams and vendor equipment drawings to first establish a final machinery arrangement. Deviations from the preliminary arrangement are noted on those diagrams to permit appropriate weight and moment calculations. Next, outfitting of all systems is performed using the outfitting system diagrams as a guide. However, a system-sequence is more or less followed in accordance with pre-assigned system priorities. For example, the main-steam system is often designed first followed by other systems requiring a great deal of space, such as vent trunks and wireways. Finally, smaller systems are added to the model. Inasmuch as pipe down to ½" is designed in this way, 90% of all engine room piping is portrayed on the model. Typically, the model scale is 1:15 and the structural portion is purchased by sub-contract. Pipes are shown in full body representation with standard items such as valves and fittings portrayed by commercially available scale-model components. The structural portion of the model is built with a tolerance of ±1 mm whereas the outfitting is built and measured on the model to ±2 mm.

Although changes can occur at any time in the design process, an attempt is made to finalize systems having high priorities at an early stage in the overall design process. In this way, fabrication in the pipe shop can commence before completion of the model. Oftentimes the model is only about 50% complete when the first pieces are fabricated.

Actual production of the piping fabrication and installation documents is performed with the model itself as a basic source of input information; no system arrangement or composites are ever prepared. Instead, outfitting systems are first divisioned off (on the model) into smaller units suitable for subassembly, fabrication and installation. Each such subassembly is then drawn freehand in the form of an isometric sketch showing dimensions (manually scaled from the model using special steel scales) and all valves and fittings identified as to type and size. Each sketch then serves as an input document to a computer-aided pipe detail program as well as an installation sketch.

Data manually extracted from the isometric sketches are entered on computer input sheets. Upon entry into the computer, these data are first checked for validity and against certain theoretical closures. If necessary, the data and/or model are modified. Once corrected, if necessary, the data for a given system are further computer-processed "in the presence of catalogs" of standard and unique parts which are defined in terms of geometry and materials. Output from this processing includes symbolic undimensioned pipe detail sketches, bending and assembly instructions, material lists, actual costs to produce each subassembly and the optimum production path to achieve efficient machine loading in the pipe shop; overloading is flagged by the computer. After isometrics are sketched at the model, about eight weeks are required to prepare the computer input and generate the installation documents for a given system.

For the purpose of outfitting, a ship is broken down into structural blocks. Hence, the isometric sketches are grouped and bound in booklets corresponding to these same blocks. Later on, these sketches are regrouped by systems for delivery to the owner in lieu of arrangement drawings. Computer generated pipe-fabrication documents, on the other hand, are bound into booklets to suit production lines in the pipe shop. Information needed to deliver finished piping according to outfitting blocks is also provided.

Development of a typical engine room model requires about 10,000 manhours, exclusive of the hull. Reportedly, regulatory agencies were initially apprehensive over the substitution of models in the place of traditional arrangement and composite drawings. Now, however, they prefer the model and generally visit it every three weeks.

3.9 "Recent Developments in the Design and Production of Marine Piping Systems" by G. Standen and D. E. Gilbert, Vickers Limited Shipbuilding Group, paper presented to the Institute of Marine Engineers, January 1977.

Several advances made over the past few years in the development of pipe production systems within Vickers are discussed. Included are the use of design models and a system for dimensioning from the models. In recent years the building program has been concentrated on naval vessels. All important areas involving pipe work are mocked up in full scale or scale model form. Information from these models was formerly lifted manually and presented as orthographic drawings or as isometric sketches. Such drawings were available early in the building program and, therefore, facilitated fabrication of pipe pieces. Pipe-bending data was calculated by computer but only after manual input of information shown on the isometrics.

To improve productivity, means for going directly from a model to the pipe fabrication documents was sought. Photogrammetry and similar techniques were investigated particularly in the chemical industry. The technique used by the Lurgi Company of Frankfort, West Germany was judged to be most suitable. Thus, basic hardware and software was purchased from Lurgi. The hardware was redesigned and software was revised to suit the special requirements of shipbuilding. The complete system is designated "CODEM" for Computer Design from Engineering Models. Even though CODEM has been designed for pipework, its extension to electrical and HVAC seems natural and is under consideration.

3.10 "RAPID Report R1; Users Manual" Preliminary -June 1977 by Newport News Shipbuilding for the National Shipbuilding Research Program.

RAPID is a software package designed to support computer-aided piping design and manufacturing documents.

Input provisions allow the user to:

- define geometry of pipe runs,
- define decision rules for selection of components,
- define assemblies and sub-assemblies, and
- define graphic output with arbitrary scales and viewing directions, and to interactively lable and dimension these drawings.

Processing on a user's request permits:

- application of decision rules for the input of pipe geometry and automatic selection of piping components,
- check for design errors by testing proposed pipe geometry against physical constraints of the pipe shop, and
- modest changes to pipe geometry to eliminate errors.

Output provisions which may be elected for collection of piping specified by the user include:

- piping drawings of any kind (with or without dimensions),
- material lists,
- pipe-bending instructions, and
- schematic (joing map) drawings.

The prototype system utilizes a minicomputer with disc storage, a magnetic tape cartridge unit, a digitizing table, a plotter/printer and a graphics cathode-ray tube. However, the software is not limited to this hardware configuration.

3.11 "Development of a New Camera for Model Engineering" by Hitachi Zosen, Hitachi Shipbuilding and Engineering Company, Ltd., October 1977.

Use of an engineering model as an aid for outfitting of piping is not necessarily restricted to placement of the model at the locations where the outfitting takes place. Photographs of the model suffice. But, because drawings will be needed for modification of follow-on ships and for future design data, the photographs should accurately convey information such as found in conventional arrangement or composite drawings. In response to the need for a means to economically produce accurate photographs (i.e. totally free of perspective distortion) Hitachi and the Japan Ship's Machinery Development Association jointly developed a scanning camera which is now known as "Draft-Camera."

In operation, a model section is placed on a moving table beneath the camera lens which is fixed. The film inside the camera also moves but in a direction opposite to that of the model. Relative speeds of the model and film are synchronized so that the recorded image is not blurred. To eliminate perspective distortion in the image, the field of view of the lens is drastically restricted by means of a masking slit placed behind the lens near to the plane of the film. Hence at any instant in time, the image recorded is a very small "patch" formed by nearly parallel rays and whose shape is that of the slit. As the model and film move synchronously, these tiny patches are imaged continously, forming a swath or strip of imagery. Once limits of the model have been passed, the instrument is momentarily halted, the table containing the model and film are both stepped sidewise (i.e. perpendicular to scanning direction) and another parallel scan is made going in the opposite direction. This "step and scan" process is continued until the entire model has been photographed.

To facilitate production of these ortho-photographic composite drawings, it is recommended that the model be built up in the same manner as planned for erection and outfitting of the actual ship. For example:

- the hull of the model should be sectionalized by deck levels; orthophotographs should be produced after completion of piping on and under decks to reflect contemplated outfitting on-block,
- outfit units should be made separately, photographed and then inserted into the model, and
- the completed model should be photographed for general overall arrangements

Typically, an orthophotographic negative produced by the Draft-Camera is further processed to produce the following:

- enlarged positive,
- enlarged negative,
- overlay containing desired dimensions, notes, balloons, etc.,
- positive of the composite, and
- Diazo reproduction of the outfitting drawing.

Tests verified that the accuracy and resolution achieved are quite adequate for shipbuilding. The photo drawing is superior to other type drawings as an outfitting aid.

3.12 *"Ten Years Experience with the Building of Scale Models" by P. Kayser, H. Sennert and K. Stulpner (in German), published in Zentralorgan fur Schiffahrt-Schiffbau-Hafen, Heft 14, 1977.*

A general overview of the development of design modeling for the shipbuilding industry (particularly German) is presented. Discussions of anticipated future advancements cover mechanization of the "take-off" from design models. Tl Vickers CODEM system is outlined.

3.13 *"Development of the Draft Camera - A New Came for Orthographic Photo Drawings" by Yukio Tomit Hitachi Shipbuilding & Engineering Co., Ltd., Japa Proceedings of The American Engineering Model Soc ety May 1979 Seminar in San Francisco, California.*

An abstract of this paper is not provided because i substance is included in other abstracts; see Parts 3.4 and 3.: of this appendix. However, this paper is an excellent compil tion of the information contained in the other papers ar describes the orthographic camera in greater detail.

3.14 *"Making an Accurate Orthographic Projection From Model" by Ari Elo; Elomatic Oy, Finland; Proceedin of The American Engineering Model Society May 19 Seminar in San Francisco, California.*

The use of design modeling in Finland began in the ear 1970s with the design of ships' engine rooms. Since then modeling has been utilized in the design of 22 machiner spaces. Elomatic Oy has been responsible for eight of these Since 1975, research has been conducted with a view towar reducing the drafting work associated with the model. Ir vestigation of several alternates led to the decision to produc true orthographic photographs (i.e. without perspective which would subsequently be digitized for transposition int a computer.

The prototype orthographic instrument now employe utilizes a laser device whose beam is projected in horizonta planes across a model section which remains stationary Upon reaching the end of one such "scan," the beam i stepped vertically by a small amount and the horizontal sca is repeated. Light reflected back from the model is collecte by a photo cell and, after amplification, varies the intensity o a light-emitting diode. The diode moves across a stationar film in the same fashion as the laser beam scans the model Hence, the resulting negative is at a scale of 1:1 relative to th model. The maximum negative (and model) size is 32 x 21 inches. Continuing efforts will be concentrated in three areas

- development of model building techniques (especially sec tionalizing) to best suit the orthophotographic process,
- development of a table for rotating a model in order to obtain different orthographic views, and
- development of a device for simultaneously digitizing from different orthographic views so that three dimensiona coordinates can be directly put into a computer.

3.15 *"The development of a 3-Dimensional Model Take-Of System" by K. W. Nichols, D. E. Gilbert and M. R. Smith, Vickers Shipbuilding Group Limited, presentec to the symposium "Computer Applications in the Automation of Shipyard Operations and Ship Design," University of Strathclyde, Glasgow, Scotland, June 1979.*

In the ship design process, it has been shown that humar work such as decision making, discussion and meetings account for only ⅓ of the total work expended. The remaining ⅔ of the work involves mechanical functions such a documentation, calculation, information retrieval, filing drawing and data transfer. Since the bulk of the design effort s mechanical in nature, computer automation of the design process can lead to improved productivity.

In the area of synthetic arrangement design, Vickers has chosen not to develop two other demonstrated systems. One would utilize minicomputer based interactive work stations for inputting synthetic-arrangement design information from drawings. The other is development of arrangements entirely within the computer. While the methods are useful for demonstration, omission of features such as hangers, space allowances for valves, fittings and minor structures cause difficulties. These applications are also limited by time and data-storage requirements.

Because of the above described shortcomings and the need to have close cooperation of mechanical, electrical and ventilation engineering disciplines in outfit planning, Vickers has developed a design modeling capability. It is employed on all first-of-class ships. A model is typically of scale 1:5 or 1:10 and shows most major and minor structures, all equipment, fittings, pipework, cables and ventilation ducts. It is considered that such models are the most practical available solution for synthetic-arrangement design where the design is totally dependent upon designers' judgments. The method not only allows visual detection of interferences, but also allows their resolution without fear of introducing new interferences.

Having created a design by means of a model, the problem then presents itself as to how to extract the dimensional data quickly and accurately so that production documents may be prepared for manufacture and installation work. Vickers' solution is the CODEM (Computerized Designs from Engineering Models) system. There are two distinct parts of the system. The first is a 3-dimensional optical measuring system linked to a mini-computer. This part of the system is used to create a data base of design information. The second part of CODEM is a mainframe software system which operates on the data base to produce a variety of output formats. The marriage of these two parts of CODEM is simply via magnetic tape.

Operation of the measuring system is as follows. Once a model section is complete it is placed upon a table, two sides of which are paralleled by two servo-drive lead screws which are at right angles to one another. A telescope may be traversed along each lead screw and also raised and lowered in elevation by a similar lead-screw arrangement. After first sighting both telescopes on a datum point on the model, locations of the telescopes are continuously monitored by the minicomputer via encoders attached to the lead-screws. When any other particular point of interest on the model is sighted, coordinates of the point (as determined by the encoded locations of the telescopes) are recorded on magnetic tape through the minicomputer. The actual command to record is issued by an operator who sits at a video unit where coordinates are simultaneously displayed. This operator also keys in descriptive data as a point's coordinates are recorded. After a magnetic tape is completed, it is taken to a mainframe computer where it is copied into a data base.

The balance of this paper describes a system of computer programs which operates upon the data base created by CODEM supplemented by data taken from steelwork drawings. Possible calculations and outputs are:

- pipe pressure and temperature loss calculations,
- pipe stress analysis,
- pipe isometrics and parts lists,
- pipe arrangement and composite drawings,
- installation control,
- digitized pipe bending information,
- cable routing and sizing,
- cable diagrams and lists,
- ventilation drawings and parts lists,
- equipment arrangement drawings,
- equipment parts lists,
- technical illustrations,
- center of gravity calculations, and
- structural drawings.

APPENDIX C SOURCES FOR HARDWARE & SERVICES

Most photogrammetric work relates to aerial mapping which, compared to land-based industrial applications, constitutes nearly the entire market for photogrammetric hardware and services. Thus, hardware vendors, in particular, are not apt to be knowledgeable about photogrammetric applications in the shipbuilding industry. As a general rule, they should not be relied upon to recommend procedures and hardware selections.

Similarly, most photogrammetric service firms work from aerial surveys for the purpose of producing planimetric and topographic maps. While they can conceivably work with land-based photography, they generally lack experience in the kind of planning and implementation that is unique and prerequisite for industrial applications. Inappropriately, such firms tend to apply equipment and software designed primarily for aerial work. However, there are aerial-survey firms having experience with industrial photogrammetry. Those known to have pertinent experience, even limited, are listed herein.

The few firms known to specialize as photogrammetic consultants are separately listed as an aid for design agents and shipbuilders contemplating in-house photogrammetric capabilities.

For further guidance, estimated first costs for photogrammetric hardware are also included.

Information about the construction and use of models can be obtained from:

American Engineering Model Society
P.O. Box 2066
Aiken, South Carolina 29801
(803) 649-6710

The only known supplier of model components suitable for ships' machinery spaces is:

Engineering Model Associates, Inc.
1020 S. Wallace Place
City of Industry, California 91748
(213) 912-7011

HARDWARE MANUFACTURERS (circa 1980)

FIRM	PRODUCTS MARKETED
Wild Heerbrugg Instruments, Inc. 465 Smith Street Farmingdale, New York 11735 (516) 293-7400	cameras analog stereoplotters
Galileo Corporation of America 36 Church Street New Rochelle, New York 10801 (914) 576-3604	cameras analog stereoplotters computer-controlled stereoplotters
Zena Company P.O. Box 338 South Plainfield, New Jersey 07080 (201) 754-4109	cameras analog stereoplotters comparators
Kern Instruments, Inc. Geneva Road Brewster, New York 10509 (914) 279-5095	stereoplotters comparators computer-controlled stereoplotters
O.M.I. Corporation of America 1319 Powhatan Street Alexandria, Virginia 22314 (703) 549-9191	computer-controlled stereoplotters
Keuffel & Esser Company 7816 Jones Maltsberger Road San Antonio, Texas 78216 (512) 822-4232	comparators computer-controlled stereoplotters
Carl Zeiss, Inc. 444 Fifth Avenue New York, New York 10018 (212) 730-4400	cameras analog stereoplotters computer-controlled stereoplotters comparators
Danko Arlington, Inc. Kelsh Instrument Division 4800 East Wabash Avenue Baltimore, Maryland 21215 (301) 664-8930	cameras analog stereoplotters
Autometric Inc. 5205 Leesburg Pike, Suite 1308/Skyline 1 Falls Church, Virginia 22041 (703) 998-7606	computer-controlled stereoplotters
Helava Associates, Inc. 21421 Hilltop Street Southfield, Michigan 48034 (313) 352-2644	computer-controlled stereoplotters
Matra Technology Inc. 120C Albright Way Los Gatos, California 95030 (408) 866-6606	computer-controlled stereoplotters
Systemhouse, Inc. 700 Princess Street, Suite 2 Alexandria, Virginia 22314 (703) 549-8488	computer-controlled stereoplotters

SERVICE FIRMS[1]
(circa 1980)

john f. kenefick Photogrammetric Consultant, Inc.[2] P.O. Box 3556 Indialantic, Florida 32903 (305) 725-2715 (305) 723-8515	computer programming fully-analytical photogrammetry analog and semi-analytical photogrammetry[3]
Henderson Aerial Surveys, Inc. 5125 West Broad Street Columbus, Ohio 43228 (614) 878-3925	analog photogrammetry semi-analytical photogrammetry fully-analytical photogrammetry
Bosworth Aerial Surveys, Inc. 4057 Lake Worth Road Lake Worth, Florida 33460 (305) 965-4477	analog photogrammetry semi-analytical photogrammetry fully-analytical photogrammetry
LaFave, Huntley, White and McGivern 850 Hudson Avenue Rochester, New York 14621 (716) 467-1010	analog photogrammetry
Koogle & Pouls Engineering, Inc. 8338 A Comanche, N.E. Albuquerque, New Mexico 87110 (505) 294-5051	analog photogrammetry semi-analytical photogrammetry fully-analytical photogrammetry
Woolpert Consultants 2324 Stanley Avenue Dayton, Ohio 45404 (513) 461-5660	analog photogrammetry semi-analytical photogrammetry fully-analytical photogrammetry
Aero-Metric Engineering, Inc. 4708 N. 40th Street Sheboygan, Wisconsin 53081 (414) 457-3631	analog photogrammetry fully-analytical photogrammetry
Geodetic Services, Inc.[2] P.O. Box 3668 Indialantic, Florida 32903 (305) 724-6831	computer programming fully-analytical photogrammetry

[1]This listing includes firms believed to have fairly recent pertinent experiences in the indicated areas. However, in several instances, the depth of these experiences is not known. Additional information may be solicited from the American Society of Photogrammetry, 105 North Virginia Avenue, Falls Church, Virginia 22046; (703) 543-6617.
[2]Specializes in and actively seeks out industrial photogrammetric work.
[3]Stereoplotter work is subcontracted.

CONSULTING FIRMS[1]
(circa 1980)

john f. kenefick
Photogrammetric Consultant, Inc.
P.O. Box 3556
Indialantic, Florida 32903
(305) 725-2715
(305) 723-8515

Donald R. Graff, P.E.
Consultant in Surveying and Mapping
P.O. Box 311
Beaver Dam, Wisconsin 53916
(414) 885-9191

LeFave, Huntley, White and McGivern
850 Hudson Avenue
Rochester, New York 14621
(716) 467-1010

ESTIMATED FIRST-COSTS FOR PHOTOGRAMMETRIC HARDWARE
(circa 1980)

Item	Analog-Stereodigitizer System Used for Demonstration		More Efficient & Cheaper Computer-Controlled Stereodigitizer System	
Camera	Wild P31	$ 23,000	Zeiss Jena	$ 30,000
Monocomparator	Kern MK2	28,000		N/A
Minicomputer	Data General or Digital Equip. Corp.	28,000		N/A
Stereoplotter	Wild A10	190,000	Bendix US2	110,000
TOTALS		$269,000		$140,000

[1]Available on a paid consulting basis. The first listed has experience in shipbuilding.